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LA JOLLA, CALIFORNIA
June, 1951

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Contribution No. 435

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Volume 40, No. 2, February 15, 1950

ZOOLOGY.—*Nemerteans from Antarctica and the Antarctic Ocean.*[1] WESLEY F COE, Scripps Institution of Oceanography. (Communicated by F. A. CHAC Jr.)

The collections of the United States Navy Antarctic Expedition in 1947–48 contained 75 specimens of nemerteans. These were dredged at several stations or collected along the shore of one of the islands in Marguerite Bay, Antarctica, near Peter I Island, Ross Island, and Cape Ross, by F. C. Nutt. Marguerite Bay is between Alexander I Island and Adelaide Island (68°–69°S., 68°–70°W.). It has a depth of 70 to 80 meters at the stations where the nemerteans were dredged. The collections indicate that the bay has a rather abundant nemertean fauna in spite of a water temperature of −1°C. or lower.

Although the collection includes only those species that have been previously described from the Antarctic region, the known geographical range is hereby extended and additional information relative to the morphological characteristics of the species has become available.

The species represented have been identified as: *Lineus corrugatus* McIntosh, 54 specimens; *Amphiporus gerlachei* Bürger, 1 specimen; *A. spinosus* Bürger, 1 specimen; *Tetrastemma amphiporoides* Bürger, 7 specimens; *T. validum* Bürger, 12 specimens. These specimens are deposited in the U. S. National Museum.

Order PALEONEMERTEA

No representatives of this order were obtained by the Navy Expedition, and only two species have been reported from Antarctic regions. These are *Carinina antarctica* Bürger, 1904, and *C. mawsoni* Wheeler, 1940.

Order HETERONEMERTEA

Lineus corrugatus McIntosh, 1887

Cerebratulus corrugatus Hubrecht, 1887; *C. steinini*, *C. subtilis*, *C. validus* Bürger, 1893; *C. charcoti* Joubin; *C. autrani* Joubin, 1908; *L. corrugatus* Baylis, 1915; *L. corrugatus* Wheeler, 1934, 1940.

This species is so highly variable both in form and color that it is not surprising that the vari ties were formerly considered to represent sep rate species. The worms are capable of an unusu degree of extension and contraction in life an on being placed in preserving fluid contract int a great variety of shapes. Consequently shape head and length of cephalic grooves, as well position and size of mouth, offer little evidenc as to their specific identity. As a result, sever different names have been given to the preserve specimens in the different collections. The speci has usually been placed in the genus *Cerebratulu* but the study of many living individuals b Wheeler (1934) proves that they have the essen tial characteristics of *Lineus*.

Colored figures of the living worms publishe by Wheeler show that the body is smooth an moderately flattened and elongated in life, a though the preserved specimens are often so co spicuously wrinkled as to have justified th species name *corrugatus*.

The color in life varies in many shades of gra pink, brown, and dark reddish brown or blac ventral side paler. A pair of white vertical ban is usually more or less conspicuous near the po terior ends of the cephalic grooves. Region proboscis opening and borders of cephalic groov pale gray or white. Similar in most respects *Lineus magelhaensicus* but differs in lacking ocel

Individuals of this species often reach a si greater than that of any other known nemertea of the Antarctic region. The length may som times exceed 50 cm. when fully extended, and th width 3 mm. After preservation the body usual contracts to a small fraction of this length, but th width may be increased to 15 mm. The large preserved specimen in the Navy Expeditic collection was 90 mm long and 8 mm wide. Son specimens remain with relatively little contra tion, with smooth bodies, narrowly pointed hea and long cephalic grooves. More frequently, ho ever, the body is so strongly contracted that th surface is roughly furrowed and corrugated, wi the head withdrawn and the cephalic groov correspondingly short.

Geographical distribution: This is evident the most abundant and most widely distribut of all the Antarctic species. Wheeler (1934) co lected several hundred specimens at South Ge gia, South Shetlands, South Orkneys, Anvers Island, East Falkland Island, and from dredge hauls at intermediate stations. The species was found from low water mark to a depth of 270 meters.

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[1] Contributions from the Scripps Institution of Oceanography, new ser., no. 435. Received July 18, 1949.

On the Navy Antarctic Expedition this species was collected at the following stations by D. C. Nutt: Off Cape Royds, Ross Island, January 29, 1948, 116 meters, 8 specimens; Marguerite Bay, February 22, 1948, 80 meters, 37 specimens; Marguerite Bay, February 20, 1948, 70 meters, 9 specimens.

The following additional representatives of this order have been reported previously from South Georgia, Falkland Islands, and from dredging stations in the South Atlantic and Antarctic Oceans: *Baseodiscus antarcticus* Baylis, 1915; *Parapolia grytvikenensis* Wheeler, 1934; *Lineus longifissus* (Hubrecht), 1887; *L. scotti* Baylis, 1915 (*L. roseocephalus* Wheeler); *L. magelhaensicus* Bürger, 1895; *Cerebratulus johnstoni* Wheeler, 1940; *C. larseni* Wheeler, 1934; and *C. malvini* Wheeler, 1934.

Order Hoplonemertea

Amphiporus gerlachei Bürger, 1904

A. gerlachei Wheeler, 1934.

The body is moderately slender and pink or rosy in color. Length of body 16 to 25 mm, width 2 to 3 mm. Bürger (1904) has published a colored figure of the living worm. Each side of the head is provided with two groups of large ocelli. The cerebral sense organs are large and are situated beside the brain. The armature of the proboscis consists of a relatively large, pear-shaped basis and 2 pouches, each containing 2 to 7 accessory stylets. There are 12 proboscidial nerves.

Geographical distribution: The specimen studied by Bürger was dredged near the ice shelf west of Charcot Island at a depth of about 500 meters. The considerable number examined by Wheeler (1934) came from depths of 161 to 208 meters in the vicinity of the Falkland Islands. The single specimen collected by D. C. Nutt on the Navy Antarctic Expedition was dredged at a depth of 80 meters near Marguerite Island. At all these localities the species was associated with *Lineus corrugatus.*

Amphiporus spinosus Bürger, 1893

A. spinosus Wheeler, 1934, 1940.

Examination of a large number of living individuals by Wheeler (1934) convinced him that this species is more variable morphologically than any other member of the genus at present known. Particularly variable are the number of pouches of accessory stylets in the proboscis and the number of proboscidial nerves. According to Wheeler's report, the accessory pouches in different individuals may vary from 2 to 22, with 1 to 3 stylets in each. If numerous, they may occupy the entire circumference of the proboscis. He found the number of proboscidial nerves to vary from 11 to 26.

The body is nearly cylindrical and may reach a length of 180 mm. The color in life is stated to be pale pink, pinkish red, brick red, or orange. Ocelli are minute but very numerous, occurring as a broad, dense patch on each side of head anterior to brain, with a few others scattered on dorsal side of brain region.

Wheeler (1934) concluded that the great variability in the proboscis armature is responsible for the several specific names that the species has been given by Bürger and Joubin. He has listed *A. spinosissimus* Bürger, *A. cruciatus* Bürger, and *A. multihastatus* Joubin as synonyms. Since in all the other known species of this genus there is relatively little variability in the proboscis armature, it may be suspected that further study of living material will prove that one or more of these names actually represent valid species.

Geographical distribution: The species has been collected over a wide area in the Antarctic. It was found in abundance among kelp holdfasts at South Georgia, and has been dredged at depths of up to 270 meters in the adjacent seas. One specimen was dredged by the Navy Antarctic Expedition off Cape Ross at a depth of 116 meters, January 29, 1948.

Tetrastemma amphiporoides Bürger, 1893

This species was first described by Bürger (1893) from South Georgia but was not mentioned by Wheeler (1934). Seven specimens were obtained by the Navy Antarctic Expedition. Each of these is about 20 mm long and 3 mm in width. The body is slender and flattened, with four large ocelli on the head. Bürger describes the color in life as dark violet dorsally and orange on ventral surface. In color the species is similar to *T. validum*, but the shape of body, general appearance, and internal anatomy differ. The armature of the proboscis consists of a conical basis, of approximately equal length to the sharply pointed central stylet, and two pouches with usually four stylets in each. There are 10 or 12 proboscidial nerves.

Geographical distribution: Dredged by the Navy Antarctic Expedition near Peter I Island at a depth of 60 meters by D. C. Nutt, February 15, 1948. Previously known only from the island of South Georgia.

Tetrastemma validum Bürger, 1893

T. validum Wheeler, 1934, 1940.

In form and color this is one of the most easily recognized of all species of nemerteans. The body is short and stout; rounded dorsally and flattened ventrally. The head is acutely pointed and separated from body by transverse lateral grooves. Color of dorsal surface is dark brown, with tinge of red, yellow, or purple. Ventral surface white, pale gray, pinkish or yellowish. In region of cephalic grooves the pale color of ventral surface extends dorsally to form a pair of conspicuous white lateral markings. These markings are broadly oval when body is extended but become sharply pointed dorsally when contracted. The internal anatomy is described in detail by Wheeler (1934), with a colored figure showing the characteristic markings of the living worm.

Twelve specimens of this species were collected by D. C. Nutt along the rocky shore of an island in Marguerite Bay. These specimens varied from 5 to 24 mm in length after preservation, although some of the living individuals mentioned by Wheeler (1934) were 35 to 40 mm long and 2.5 mm in width.

Geographical distribution: This is evidently a common species in the Antarctic region, for it has been collected also in Bransfield Strait, South Shetlands, at a depth of 200 meters, and in shallow water in the Palmer Archipelago, as well as near King Edward Cove, South Georgia (Wheeler 1934). Bürger first described the species from South Georgia.

The following additional representatives of this order have been reported from South Georgia, Falkland Islands, and the Antarctic region:

Amphiporus falklandicus Wheeler, 1934.
  inexpectatus Wheeler, 1934.
  lecointei Bürger, 1904.
  marioni Hubrecht, 1887.
  moseleyi Hubrecht, 1887 (*A. racovitzai* Bürger).
  schollaerti Wheeler, 1934.
  scoresbyi Wheeler, 1934.
Tetrastemma antarcticum Bürger, 1893.
  duboisi Bürger, 1893.
Tetrastemma esbenseni Wheeler, 1934.
  georgianum Bürger, 1893.
  gulliveri Bürger, 1893.
  hansi Bürger, 1893.
  longistriatum Wheeler, 1934.
  maivikenensis Wheeler, 1934.
  stanleyi Wheeler, 1934.
  unilineatum Joubin, 1910.
  weddelli Wheeler, 1934.
Nemertopsella marri Wheeler, 1940.
Drepanophorella tasmani Wheeler, 1940.

It will be observed that among these 35 species at present known from the Antarctic, the only representatives of the Paleonemertea are 2 species of *Carinina*, although the Heteronemertea are represented by 9 species and the Hoplonemertea by 24 species. In comparison, there are 53 species recorded from the Atlantic coast of North America, of which 5 are paleonemerteans, 19 heteronemerteans, 28 hoplonemerteans, and 1 bdellonemertean. On the Pacific coast of North America there are 98 known species; 11 of these are paleonemerteans, 37 heteronemerteans, 49 hoplonemerteans, and 1 bdellonemertean. The Antarctic nemertean fauna therefore does not differ widely from that of other regions, for with one exception the genera are identical and the proportionate representation of the species among the orders is in reasonably close agreement. All the species, however, appear to be peculiar to the Antarctic.

Although the temperature of the water remains below 0° C. even in midsummer in some of these areas, the nemertean population is almost as large and the mature individuals of approximately the same size as in related species living in regions of more moderate temperature.

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Contribution No. 436

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A STATISTICAL MODEL OF INSTANTANEOUS POINT AND DISK SOURCES WITH APPLICATIONS TO OCEANOGRAPHIC OBSERVATIONS

George F. McEwen

(Contributions from the Scripps Institution of Oceanography, New Series, No. 437)

Abstract--In general, a space distribution of particles within water, or of properties of the water, may be considered as resulting from the movements of small objects from some known or hypothetical initial position. Such displacements are regarded as the resultant of a large number of small positive or negative movements following probability laws. In the one-dimensioned case, the frequency of a resultant displacement x and the standard deviation of the positions of the moving objects are derived from a limiting form of the binomial series. This statistical equation is analogous to the solution of the differential equation of diffusion in one dimension from an initial concentration on a plane perpendicular to the x-axis. The constants in this differential equation of diffusion may be equated to the corresponding parameters of the statistical equation, thus providing a statistical interpretation of the diffusion equation. These results are generalized to the familiar two-dimensioned instantaneous point source problem. Later this is generalized to a disk source. Various applications of these solutions are made to observations of drift bottles in the sea and to temperature, salinity, and plankton concentration in certain stagnant areas of the sea, associated with large horizontal eddies. The diffusion coefficients thus obtained from concentrations changing with time, the dynamic case, agree well with those derived from a steady state corresponding to an assumed equilibrium between advection and diffusion at the boundary between water masses of different properties.

Statistical theory of space distribution of particles--Probability or chance always enters into the distribution of organisms or other objects in space, and influences all methods of collecting data about such distributions, and interpreting the results [BUCHANAN-WOLLASTON, 1938]. In general, a space distribution of objects or properties may be considered to be due to their movement from some known or hypothetical position, and it is in such movement that the element of chance will be regarded as entering. Chance may influence both the amount and direction of movement, which may be in one, two, or three dimensions.

The principle may be illustrated by considering first the simplest case of pure random movement of objects in one direction only. This movement may be considered as the sum of a great number of small equal movements, each of which is equally likely to be in one direction or in the opposite direction; for example, to the right or to the left. Then the space distribution of N objects after n "chances" of movement will be given by the terms of the expansion of the binomial $N(1/2 + 1/2)^{2n}$.

The frequency, $F_{m,(2n-m)}$, of m movements to the left and (2n-m) movements to the right is given by the (m+1)st term,

$$F_{m,(2n-m)} = N\,(1/2)^{2n}\,\lfloor\underline{2n}/\lfloor\underline{m}\,\lfloor\underline{2n-m},\ [L^{m}R^{2n-m}] \ldots\ldots\ldots\ldots \quad (1)$$

where the exponents in this descriptive expression [ ] equal respectively the number of movements to the left and to the right.

In practical applications of diffusion we are concerned with large values of n, and use a well-known approximation to the term $F_{m,(2n-m)}$ of the binomial expansion,

$$F_{m,(2n-m)} = N\,(1/2)^{2n}\,\lfloor\underline{2n}/\lfloor\underline{m}\,\lfloor\underline{2n-m} \sim Ne^{-[(n-m)^2/n]}/\sqrt{\pi n} \ \ldots\ldots\ldots \quad (2)$$

The approximation is closer the larger the value of n.

Consider the frequency F_x of a resultant of $x/h = (n-m)$ movements to right or to the left. x equals the resultant distance and x = 0 corresponds to the origin where there are n movements to the right and m to the left. Substitute in the approximate expression and use the equality sign, since we are concerned with large values of n. The result is

$$F_x = Ne^{-(x^2/nh^2)}/\sqrt{\pi n} \qquad (3)$$

which is the frequency of a resultant of x/h movements over an elementary distance h or of a resultant distance x, expressed in terms of h as a unit.

In the binomial series $(1/2 + 1/2)^{2n}$ the mean equals n and the standard deviation equals $\sqrt{n/2}$

$h\sqrt{n/2} = \sigma h$ is defined as the spread of the moving objects, or the standard deviation of the di tance through which they have moved.

The whole range of the distribution is given by the number of terms of the binomial; it extend from n units to the left to n units to the right of the center, and including the center space, is 2n + units in length. The total number of movements, 2n, is evidently proportional to the time during w the objects are subject to movement.

Therefore, the spread, $h\sqrt{n/2}$, from the center is proportional to the square root of the time a may accordingly be written

$$\text{Spread} = h\sqrt{(n=ct)/2} = \sqrt{kt} = h\sqrt{n/2} = \sigma \qquad (4)$$

where c equals number of movements per unit time. The coefficient k depends upon the conditions of movement. Also $\sqrt{k} = h\sqrt{c/2}$ or $k = h^2(c/2) = L^2/T$, $\sqrt{n} = (\sqrt{2}/h)\sqrt{kt}$, and

$$F_x = Nhe^{-(x^2/2kt)}/\sqrt{2\pi kt} \qquad (5)$$

where $\sqrt{kt} = \sigma$, the standard deviation of the distance of the particles from the origin.

The integral from $-\infty$ to $+\infty$ of the frequency F_x of the number of particles with respect to the number of movements should equal N, the total number of particles. This result is verified by eva uating the following integral

$$\int_{-\infty}^{\infty} (F_x)h^{-1}dx = (1/h)Nh\int_{-\infty}^{\infty} [e^{-(x^2/2kt)}/\sqrt{2\pi kt}\,]dx \qquad (6)$$

We shall now compare appropriate solutions of the differential equation of diffusion and heat conduction with the above expression for F_x in order to obtain a physical interpretation of the coefficients of diffusion and heat conduction. From laboratory experiments

$$dm = \alpha^2 A(\partial S/\partial x)dt \qquad (7)$$

where dm equals the amount of substance that diffuses through the area A in time dt, S equals conc tration of the substance or mass per unit volume of the solution, and α^2 equals the coefficient of di fusion.

The following diffusion equation in one dimension may be derived from the above principle,

$$\partial S/\partial t = \alpha^2 \partial^2 S/\partial x^2 \qquad (8)$$

where α^2 is the coefficient of the diffusion and has the dimension L^2/T.

To compute the dispersion from an instantaneous source of material we must obtain an appropriate solution of the diffusion equation. The solution

$$S = (1/2\alpha\sqrt{\pi t})\int_{-\infty}^{\infty} f(\lambda)e^{-(\lambda - x)^2/4\alpha^2 t}d\lambda \qquad (9)$$

reduces to f(x) for t = 0.

Consider a thin section at distance λ and of thickness Δλ. Material is suddenly distributed through the section so that there are M grams in a volume of unit area and thickness Δλ.

Then at time t = 0, S is the concentration or mass per unit volume in this section and equals M/Δλ; S = 0 at all other sections. Therefore

$$S = (1/2\alpha\sqrt{\pi t})\int_{\lambda}^{\lambda + \Delta\lambda} (M/\Delta\lambda)e^{-(\lambda - x)^2/4\alpha^2 t}d\lambda \qquad (10)$$

$$\lambda < \lambda' < \lambda + \Delta\lambda$$

$$S = (1/2\alpha\sqrt{\pi t})\,(M/\Delta\lambda)e^{-(\lambda' - x)^2/4\alpha^2 t}\,\Delta\lambda \quad \ldots\ldots\ldots\ldots \quad (11)$$

As $\Delta\lambda$ approaches zero, this reduces to

$$S = Me^{-(x^2/4\alpha^2 t)}/2\alpha\sqrt{\pi t} \quad \ldots\ldots\ldots\ldots \quad (12)$$

if the origin is at $\lambda = \lambda' = 0$. The integral of this value of S from $-\infty$ to $+\infty$ should equal the total amount of material M, as the following computation shows

$$\int_{-\infty}^{\infty} S dx = (M/\sqrt{\pi})\int_{-\infty}^{\infty} e^{-(x^2/4\alpha^2 t)} d(x/2\alpha\sqrt{t}) = M\left\{(1/\sqrt{\pi})\int_{-\infty}^{\infty} e^{-B^2} dB\right\} = M \quad \ldots\ldots \quad (13)$$

Similarly for an instantaneous heat source the differential equation is

$$\partial\theta/\partial t = a^2 \partial^2\theta/\partial x^2 \quad \ldots\ldots\ldots\ldots \quad (14)$$

where the thermometric conductivity is a^2. The solution is

$$\theta = Qe^{-(x^2/4a^2 t)}/2a\sqrt{\pi t} \quad \ldots\ldots\ldots\ldots \quad (15)$$

where

Q = strength of the source = $q/\rho c$,
q = units of heat per unit area suddenly generated at the source, $x = 0$,
ρ = density of the material,
c = specific heat,
$1/\rho c$ = rise in temperature caused by one unit of heat.

The correctness of each of these solutions, S and θ, can be shown by substitution in the differential equation.

On comparing (5) the expression of frequency

$$F_x = Nhe^{-(x^2/2kt)}/\sqrt{2\pi kt} \quad \ldots\ldots\ldots\ldots \quad (16)$$

and the solution of (12) the differential equation of diffusion

$$S = Me^{-(x^2/4\alpha^2 t)}/\sqrt{4\pi\alpha^2 t} \quad \ldots\ldots\ldots\ldots \quad (17)$$

it is evident that $4\alpha^2 = 2k$ or $\alpha^2 = k/2 = ch^2/4$. But the standard deviation of the dispersed particles is $\sigma = \sqrt{kt} = \sqrt{2\alpha^2 t}$. Therefore α^2, the coefficient of diffusion, equals $\sigma^2/2t$, and has the dimension L^2T^{-1}.

The expression of frequency (5) divided by N is the a probability P_x, and, to consider motion in two dimensions, multiply the two corresponding equations and obtain

$$\begin{aligned} P_{xy} &= [h_1 e^{-(x^2/2k_1 t)}/\sqrt{2\pi k_1 t}][h_2 e^{-(y^2/2k_2 t)}/\sqrt{2\pi k_2 t}] \\ &= (h_1 h_2/2\pi\sqrt{k_1 k_2})[e^{-(x^2/2k_1 t) - (y^2/2k_2 t)}]/t \quad \ldots\ldots\ldots\ldots \quad (18) \end{aligned}$$

which may be compared with the solution of the differential equation of diffusion from a point source for two dimensions

$$S = (M/2\pi\sqrt{4\alpha_1{}^2\alpha_2{}^2})\,[e^{-(x^2/4\alpha_1{}^2 t) - (y^2/4\alpha_2{}^2 t)}]/t \quad \ldots\ldots\ldots\ldots \quad (19)$$

Evidently $\alpha_1{}^2 = k_1/2$, $\alpha_2{}^2 = k_2/2$, and the standard deviation in the x and y directions are respectively

$$\sigma_x = \sqrt{2\alpha_x{}^2 t} \text{ and } \sigma_y = \sqrt{2\alpha_y{}^2 t} \quad \ldots\ldots\ldots\ldots \quad (20)$$

Assuming circular symmetry and a constant coefficient of diffusion α^2, the foregoing equation for S reduces to the familiar point source solution

$$S = Me^{-(r^2/4\alpha^2 t)}/4\pi\alpha^2 t = S_1 r_1{}^2 e^{-(r^2/4\alpha^2 t)}/4\alpha^2 t \quad \ldots\ldots\ldots\ldots \quad (21)$$

where $r = \sqrt{x^2 + y^2}$ = distance from the center, S_1 = initial concentration.

Using the following definition of the standard deviation in the two-dimensioned case

$$\sigma = \sqrt{[\int_0^\infty S(2\pi r)r^2 dr]/[\int_0^\infty S(2\pi r)dr]} \quad \ldots\ldots\ldots\ldots\ldots (22)$$

and substituting for S the foregoing point source solution, with A in place of α^2, the same value is found for the standard deviation as before, namely

$$\sigma = \sqrt{2At} \quad \ldots\ldots\ldots\ldots\ldots (23)$$

Because of irregularities and lack of symmetry of the observed distribution it may be advantageous to use the proportion of material outside of a circle of radius r to the total amount

$$P = 1 - [\int_r^\infty S(2\pi r)dr]/M = 1 - e^{-(r^2/4At)} \quad \ldots\ldots\ldots\ldots\ldots (24)$$

assuming a point source.

Another formula for computing A can be derived by assuming the theoretical distribution of th material at a given instant of time to approximate closely enough to the observed distribution, if a suitable value, T_0, is substituted for the time t. T_0 equals the time from the initial condition, t = to the given instant. Let T_1 equal the time measured from the same origin to a later instant. Determine from a chart of observed distributions at any time the distance from the center of dispers beyond which no concentration can be detected. This distance would be r = λ , where according to probability theory $\lambda \sim 2.5$, and from the statistical theory $\sqrt{2AT_0} = \sigma_0 = r_0/\lambda$, $\sqrt{2AT_1} = \sigma_1 = r_1/\lambda$

From (5) and (6) the coefficient of eddy diffusion can be computed in either of two ways,

$$A = (\sigma_1^2 - \sigma_0^2)/2(T_1 - T_0) = (r_1^2 - r_0^2)/2\lambda^2(T_1 - T_0) \quad \ldots\ldots\ldots\ldots (25$$

The second expression, not involving σ, is adapted to rapid approximate estimates depending upon judgment of the distances r_0 and r_1, beyond which there is no concentration.

Equation (25) also applies to the one-dimension case, the initial concentration being along the s face, if the variable distance x, perpendicular to the surface, is substituted for r.

Application of the foregoing theory to drift bottles--Observations on drift bottles [TIBBY, 193 serve to illustrate the application of (24). Tibby lists the proportion of drift bottles released at ea of a number of stations in the Pacific off Southern California. Since recoveries were made only al the shore, it was assumed that the proportion that would be recovered outside of a circle of radius equal to the distance from the station to the shore could be determined by multiplying the listed pr portion recovered by a factor equal to the circumference of the circle, divided by the distance alo the shore where recoveries were made. Although the uncertainties due to field conditions preclud accurate results the theory was applied, and the results, presented in Table 1, appear to give valu of the coefficient of lateral eddy diffusion in general agreement with those found in the same regio from applications of different formulae to data on temperature and salinity.

Generalization of problem of diffusion from point source to disk source--It is recognized that the point source formula is of limited application to conditions in the sea. The assumptions involv very small initial area, or great distance from the center or great value of the time. Accordingly it is necessary to generalize the point source formula to permit an initial concentration over a cir cular area of any size, and valid for any values of the time and distance. This problem may be so by a method which will now be outlined [McEWEN, 1946].

Integration from 0 to ∞ with respect to λ, of the elementary solution,

$$S = F(\lambda)e^{-(\lambda^2 At)}J_0(\lambda r)$$

of the differential equation of diffusion

$$\partial S/\partial t = A[(\partial^2 S/\partial r^2) + (1/r)(\partial S/\partial r)] \quad \ldots\ldots\ldots\ldots\ldots (26$$

results in a solution subject to the boundary conditions, $S(0,r) = S_1$ for $r < r_1$ and $S(0,r) = 0$ for $r > r_1$, where r_1 is the radius of the circle of initial concentration S_1, if the arbitrary function $F(\lambda)$ is properly chosen. The resulting formal solution is

$$S = S_1 r_1 \int_0^\infty J_1(\lambda r_1)\, J_0(\lambda r)e^{-\lambda^2 At}d\lambda \quad \ldots\ldots\ldots\ldots\ldots (27$$

where J_0 and J_1 are Bessel Functions of the first kind and $F(\lambda)$ was determined from the following integral of Weber,

$$\int_0^{\infty} J_1(x) J_0(\alpha x) dx = \left\{1, \alpha^2 < 1;\ 1/2, \alpha^2 = 1;\ 0, \alpha^2 > 1\right\} \ldots\ldots\ldots\ldots (28)$$

The formal solution reduces to

$$S = S_1 \left[1 - e^{-(r_1{}^2/4At)}\right] \ldots\ldots\ldots\ldots (29)$$

and

$$S = (S_1/2) \left[1 - e^{-(r_1{}^2/2At)} I_0 r_1{}^2/2At\right] \ldots\ldots\ldots\ldots (30)$$

respectively for $r = 0$, and $r = r_1$, where I_i is the modified Bessel Function of the first kind.

To transform the general solution into one convenient for interpretation and numerical work, differentiate it with respect to r and add the integral of this result with respect to r from 0 to r to the value corresponding to $r = 0$, thus obtaining

$$S = S_1 \left[1 - e^{-(r_1{}^2/4At)}\right] - S_1 r_1/2At) e^{-(r_1{}^2/4At)} \int_0^r e^{-(r^2/4At)} I_1(rr_1/2At) dr \ldots (31)$$

Repeated integration by parts in two ways, and application of Sonine's expansion

$$[e^x + I_0(x)]/2 = I_0(x) + I_1(x) + I_2(x) + \ldots,$$

results in the following solutions

$$S = S_1 \left\{1 - e^{-(r - r_1)^2/4At} [f_0(rr_1/2At) + (r/r_1) f_1(rr_1/2At) + (r/r_1)^2 f_2(rr_1/2At) + \ldots.]\right\} \text{ for } r < r_1, \ldots\ldots\ldots\ldots (32)$$

and

$$S = S_1 e^{-(r - r_1)^2/4At} [(r_1/r) f_1(rr_1/2At) + (r_1/r)^2 f_2(rr_1/2At) + \ldots.] \text{ for } r > r_1 \ldots (33)$$

where $e^{-x} I_i(x)$ is denoted by $f_1(x)$, which varies between the limits 0 and 1 and decreases as i increases. Both expressions reduce to the particular solution already obtained, if r_1 is substituted for r. Also each series converges more rapidly than the geometrical series resulting from substituting 1 for $f_i(\ )$, since these functions decrease as i increases.

The effect of size r_1 of the initial circle of concentration on the distribution of a given mass M of material can be determined as follows: Let S correspond to an initial concentration in a circle of radius r_1, and to a given total amount of material M. Denote by S′ the concentration corresponding to the same value of M but for $r_1 \rightarrow 0$, the point source problem. Then by substituting approximations to $f_i(x)$, assuming x to be small, in the exact equation, the following approximate relation can be derived, assuming $(rr_1/2At)$ and $(r_1{}^2/4At)$ to be small < 1, and $r > r_1$

$$S \sim [1 - rr_1/2At + (7/12)(r_1{}^2/4At) - (r_1{}^2/4At)(rr_1/2At) + (11/24)(rr_1/2At)^2 + \ldots\ldots] S' \ldots\ldots\ldots\ldots (34)$$

This approximate equation can be used only if the time is sufficiently great in relation to the product of the distances rr_1. It is based upon the following approximations

$$\begin{aligned} f_0(x) &\sim 1 - x + (3/4)x^2 - (5/12)x^3 \\ f_1(x) &\sim (1/2)x(1 - x) + (11/48)x^3 \qquad \ldots\ldots\ldots\ldots (35) \\ f_2(x) &\sim (1/6)x(1 - x^2/24) f_1(x) \end{aligned}$$

corresponding to small values of $x < 1$.

Table 1--Estimates of A

Station	Proportion recovered	Factor to give proportion for complete circle	Factor times proportion[a]	$\alpha = r^2/4At$
12	0.25	2.0	0.50	0.6931
57	0.43	1.0	0.43	0.844
74	0.06	3.0	0.18	1.715
75	0.08	3.0	0.24	1.427
76	0.17	3.0	0.51	0.673
77	0.014	3.0	0.042	3.17
Median values of sta. 74-77	0.07	3.0	0.21	1.651
All stations, 5943 bottles	0.032	3.0	0.10	2.3026

[a] Factor times proportion equals observed $e^{-\alpha}$

Assuming $r_1/2A = 1$ (see Table 2)

$$S \sim [1 - r/t + (7/12)(r_1/2t) - (r_1/2t)(r/t) + (11/24)(r/t)^2 - \ldots.]S' \qquad \text{(3}$$

Therefore, if r or r_1 = 1 kilometer, only values of t > one day could be used. This equation serve to determine whether for given conditions the point source solution could be used as a sufficiently close approximation, and affords a method of correcting this solution.

Application of instantaneous disk source theory--Studies of large horizontal eddies in the oce off Southern California [McEWEN, 1948] involved the diffusion of vorticity from an initial concentr tion in large circular areas, according to (32) and (33), and implies the presence of cold stagnant areas of high salinity, roughly circular, of radii from ten to 80 km. From charts of the distributi of surface temperature and salinity at intervals of about two weeks, the relation of temperature tc distance, from the center, and of salinity was determined. From charts prepared later the relatic of diatom concentration to distance from the center was also determined. Equation (37) was fitted the relation to distance from the center at the earliest time in each case, and substitution of the s cessive times of observation in the corresponding formula provided expected values for comparis with these observations. For convenience a scale transformation of the temperature and concentr tion was made such that the equation for temperature reduced to $A(S - S_0) = 1 - [\ ]$, and the equat for concentration reduced to $B(S - S_0) = 1 + [\ ]$, where [ ] = coefficient of S_1 in (32) and (33), or t equivalent

$$\left\{1 - e^{-c} - 2c\int_0^{\theta} e^{-c(1-\theta)^2} f_1(2c\theta)d\theta\right\} \qquad \text{(37}$$

in which $c = r_1^{\,2}/4At$, $\theta = r/r_1$, $2c\theta = rr_1/2At$.

In general, the results shown in Figures 1 to 5 indicate a rough agreement between theory anc observation. Furthermore, the coefficients of eddy diffusion thus found, and presented in Table 2, are in good agreement with those determined from drift bottles, and from applications of equilibri formulae to the same region [SVERDRUP and FLEMING, 1941]. From the equation $\partial(A_y\partial S/\partial y)/\partial$ $\partial(uS)/\partial x$, where y denotes the distance perpendicular to the coast and x, the distance parallel to t coast, they found that A_y varied from (0.1 to 5) × 10^6, and averaged 2.2 × 10^6. Applying the mixin equation $A\partial^2S/\partial y^2 = u\partial S/\partial x$ to the salinity distribution, they found that A = (5 to 10) × 10^6.

According to SUTTON [1932] and SVERDRUP [1946], the coefficient of horizontal turbulence A depends principally on the scale of the phenomenon, such that A/r_1 equals about 0.4. Values of thi ratio, entered in Table 2, are in general agreement with this result.

from data on drift bottles

r		t		r^2	$4\alpha t$	Coefficient of diffusion $r^2/4\alpha t = A$
mi	cm × 10^5	day	sec × 10^5	$cm^2 \times 10^{10}$		
60	111.0	25	21.6	12321	6.0×10^6	2.08×10^7
28	51.7	13	11.2	2673	3.8×10^6	0.70×10^7
42	77.6	53	45.8	6022	31.3×10^6	0.19×10^7
30	55.5	40	34.6	3080	19.8×10^6	0.16×10^7
20	37.0	18	15.6	1369	4.2×10^6	0.32×10^7
40	74.0	52	45.0	5476	57.1×10^6	0.10×10^7
35	64.8	45	38.9	4199	25.7×10^6	0.16×10^7
30	55.5	30	25.9	3080	23.9×10^6	0.13×10^7

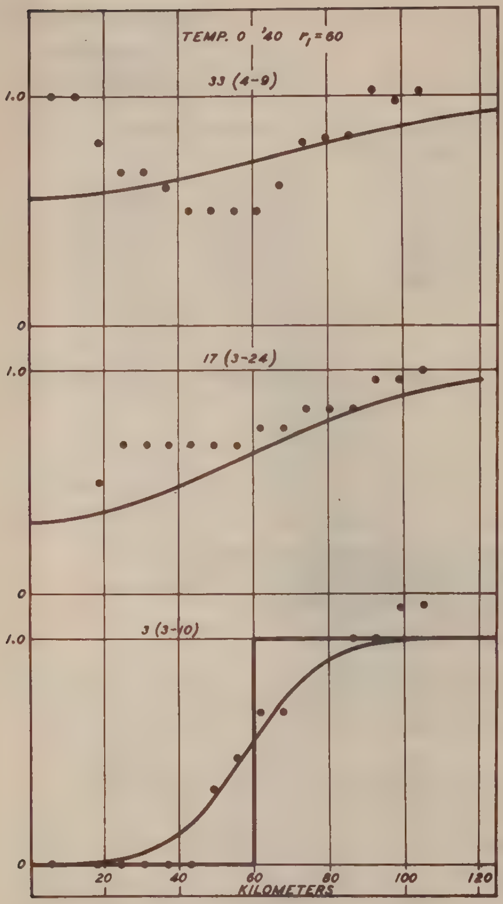
Table 2--Values of A and A/r_1 obtained from the lateral diffusion of heat, salinity, vorticity, diatoms and drift bottles from circular sources of various radii r_1 off Southern California

Diffusing material	Year	Depth	r_1	A	A/r_1
		m	km		
Heat	1940	0	60	5.5×10^6	0.9
	1941	50	80	2.1×10^6	0.3
Salinity	1941	0	60	2.9×10^6	0.5
	1941	50	70	1.6×10^6	0.2
Vorticity	1940	0	10	1.5×10^5	0.15
	1940	50	10	1.0×10^5	0.1
	1941	0	30	3.0×10^5	0.1
Diatoms	1941	0 to 60	25	1.8×10^6	0.7
Drift bottles	1937	0	point source	(1.3 to 7) × 10^6	. . .

The scale transformations used in computing A were as follows

Heat	1940	0	$0.667(S - 14.0) = 1 - [\ ]$
	1941	50	$0.286(S - 10.5) = 1 - [\ ]$
Salinity	1941	0	$4.000(S - 33.0) = 1 + [\ ]$
	1941	50	$2.860(S - 32.9) = 1 + [\ ]$
Diatoms	1941	0 to 60	$0.125(S + 7.25) = 1 + [\ ]$

The following summary of certain conclusions regarding the related subject of the mixing length is presented here for reference. From engineering experiments the ratio of the square root of the mean square deviation of velocity to the mean velocity equals $\sqrt{\bar{u}^2}/\bar{U} = \gamma$, which ratio varies between 0 and 0.1, according to A. A. Kalinske, G. I. Taylor and H. L. Dryden. From the relation $\sqrt{\bar{u}^2} = A/\rho \ell$,



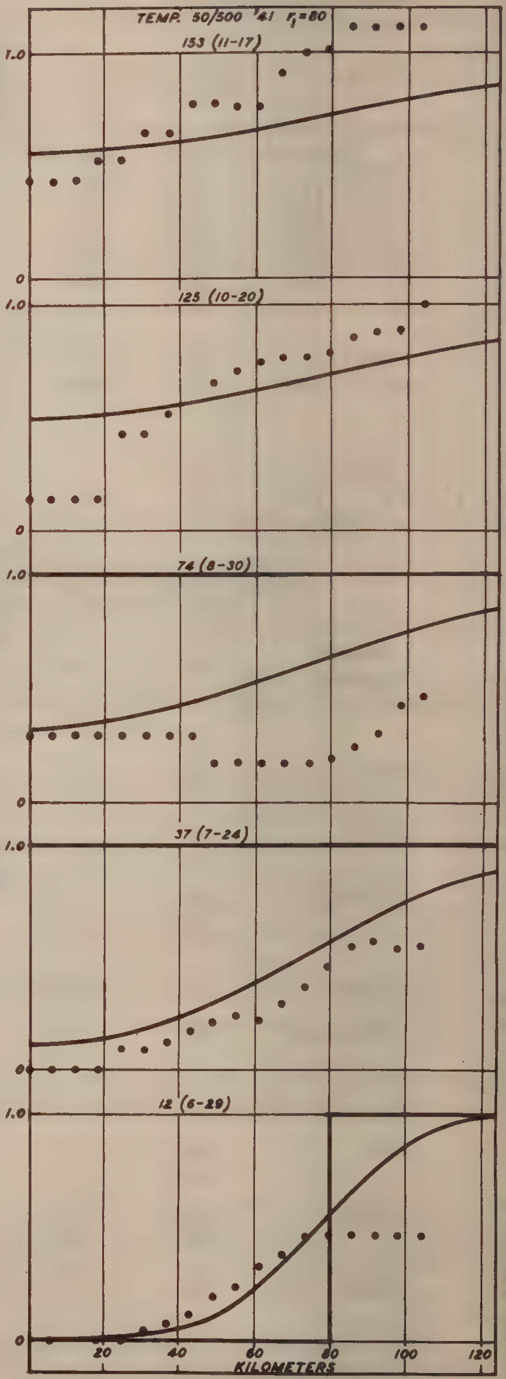


Fig. 1--Diffusion of heat into a circular area of radius r_1 kilometers and depth diameters, at indicated number of days T, from initial condition; straight lines indicate initial condition; curves, theoretical relations; and points, observations: (a) r = 60, d = 0, T = 3, 17, and 33, respectively from bottom, 1940; (b) r = 80, d = 50, T = 12, 37, 74, 125, and 153, respectively from bottom, 1941

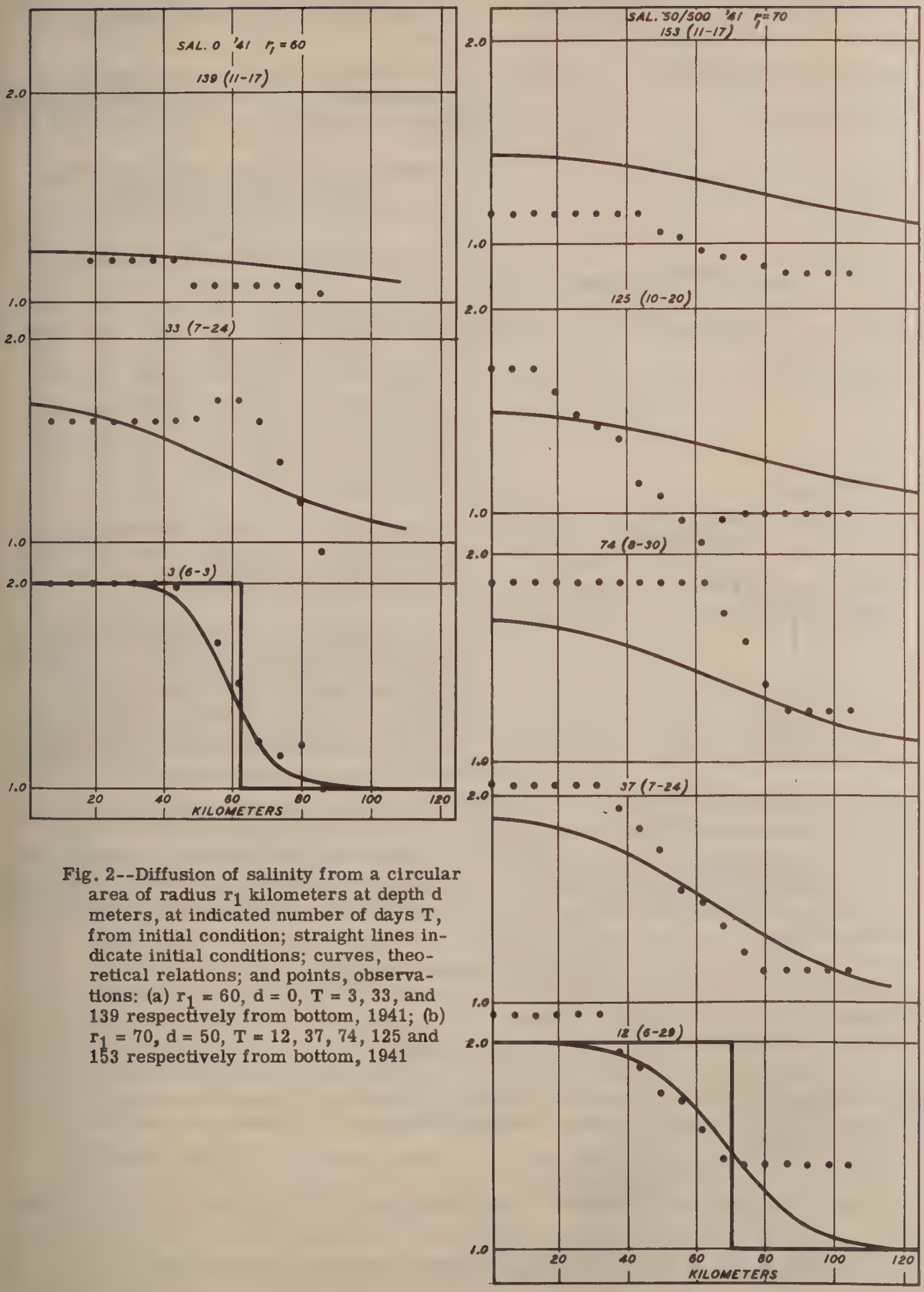


Fig. 2--Diffusion of salinity from a circular area of radius r_1 kilometers at depth d meters, at indicated number of days T, from initial condition; straight lines indicate initial conditions; curves, theoretical relations; and points, observations: (a) $r_1 = 60$, $d = 0$, $T = 3$, 33, and 139 respectively from bottom, 1941; (b) $r_1 = 70$, $d = 50$, $T = 12$, 37, 74, 125 and 153 respectively from bottom, 1941 where A equals coefficient of turbulence, ρ equals density of the fluid, the mixing length equals $\ell = A/\rho\gamma U$.

Values of ℓ, kilometers corresponding to selected values of γ, U, and A, expressed in cgs units are shown in Table 3.

Table 3--Values of the mixing length ℓ found from engineering experiments

γ	ρ	U	A				
			10^4	10^5	10^6	10^7	10^8
0.05	1.0	10	0.2	2.0	20.	200	2000
0.05	1.0	20	0.1	1.0	10.	100	1000
0.05	1.0	30	0.067	0.67	6.7	67	670
0.05	1.0	40	0.050	0.5	5.0	50	500
0.10	1.0	10	0.1	1.0	10.	100	1000
0.10	1.0	20	0.05	0.5	5.	50	500
0.10	1.0	30	0.033	0.33	3.3	33	330
0.10	1.0	40	0.025	0.25	2.5	25	250

For values of A of the order of 10^6 or less, these values of ℓ are in general less than r_1 of Table 2, and therefore less than r, corresponding to points outside of the source.

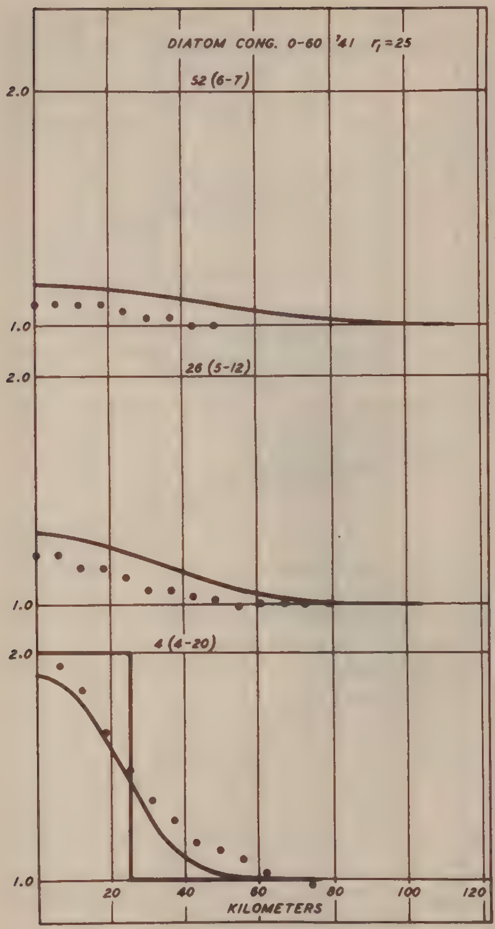


Fig. 3--Diffusion of diatoms: r_1 = 25, d = 0 to 60, T = 4, 26, and 52 respectively from bottom, 1941

Solution of the diffusion equation, assuming a variable coefficient of diffusion Br--The foregoing evidence that in the open ocean the scale of the lateral diffusion process increases with the size of the area considered suggests using a variable coefficient Br, where r equals the distance from the center of the area. The corresponding differential equation of radial diffusion is

$$\partial S/\partial t = B(r\partial^2 S/\partial r^2 + 2\partial S/\partial r) \quad . \; . \; .(38)$$

An exact formal solution of the equation, subject to the same boundary conditions as before, can be expanded into convergent series [McEWEN 1946]. At the center of the circle, r = 0, the exact solution is

$$S = S_1[1 - e^{-r_1/Bt}(1 + r_1/Bt)] \quad \ldots\ldots (39)$$

Writing

$$S = (C/t^2)\, e^{-r/Bt} \quad \ldots\ldots (40)$$

and substituting in (38) proves this value of S to be a solution for any value of the constant C. The integral, $\int_0^r S(2\pi r)dr$, equals the mass of material within a circle of radius r, and, for the foregoing value of S, becomes

$$(C/t^2)\int_0^r 2\pi r\, e^{-r/Bt}dr = 2\pi CB^2\;[1 - e^{-r/Bt}(1 + r/Bt)] \quad \ldots\ldots (41)$$

As r→∞, this approaches $2\pi CB^2$, which must equal M. Therefore $C = M/2\pi B^2$ and

$$S = Me^{-r/Bt}/2\pi(Bt)^2 \quad \ldots\ldots (42)$$

which is a special case of the general solution for $r_1 \rightarrow 0$. The mass of material within a circle of radius r, equals

$$M' = M[1 - e^{-r/Bt}(1 + r/Bt)] \quad \text{.......................} \quad (43)$$

Numerical applications of both (39) and (43) can be readily made by means of tables of the Poisson series used in statistics [MOLINA, 1942]. In his Table 2

$$P(c,a) = [1 - e^{-a}(1 + a)] \quad \text{.........................} \quad (44)$$

for c = 2, his "a" is the value of r_1/Bt in (39) or r/Bt in (43).

The square of the standard deviation equals

$$\sigma^2 = (\int_0^\infty S(2\pi r)\, r^2\, dr)/(\int_0^\infty S(2\pi r)\, dr) = 6(Bt)^2 \quad \text{..............} \quad (45)$$

for the value of S given in (42). From the same assumptions regarding times of observations as in the case of a constant coefficient of eddy diffusion

$$\sigma_0 = \sqrt{6}\, B\, T_0 = r_0/\lambda \quad \text{........................} \quad (46)$$

$$\sigma_1 = \sqrt{6}\, B\, T_1 = r_1/\lambda \quad \text{........................} \quad (47)$$

where $r = \lambda\sigma$ is the distance beyond which no concentration can be detected, and $\lambda \sim 1.5$. Therefore

$$B = (\sigma_T - \sigma_{T_0})/\sqrt{6}\,(T - T_0) = (r_T - r_{T_0})/\lambda\sqrt{6}\,(T - T_0) \quad \text{...........} \quad (48)$$

which corresponds to (25) based upon a constant coefficient. Equation (48) also applies to the one-dimensioned case, the initial concentration being along a plane, if the variable x, perpendicular to the surface, is substituted for r, $\sqrt{2}$ is substituted for $\sqrt{6}$, and $\lambda \sim 3.5$.

Preliminary applications of the foregoing formulas, based upon a coefficient of diffusion varying in proportion to the distance from the source, have been made with the aid of dye bombs and the observed distribution of the ammonia concentration due to the discharge of water from a sewage treatment plant. Experiments with these relatively small scale diffusion phenomena supported the theoretical relation and suggest the need of further investigations.

Concluding remarks--A simple statistical model of diffusion phenomena was found to agree with solutions of the differential equation of diffusion, and serves to interpret the coefficients in these solutions. Moreover, the statistical approach suggested alternative methods of obtaining approximate values of the diffusion coefficient from field observations, under certain restrictions regarding time and distance, on the assumption of point sources even though the actual sources were areas. Generalized solutions of the differential equation, corresponding to an initial circular area of any size, make it possible to devise a model conforming in essential features to actual conditions, for both constant and variable coefficients of diffusion. The coefficients obtained from applications of these dynamical methods involving variations with time were consistent with earlier values based upon different formulas adapted to equilibrium conditions. Since applications were made to observations averaged over periods of time, several hours or days in length, the analogy to molecular diffusion expressed by Fick's equation used a generation ago by Taylor and Schmidt, should serve in describing these ocean phenomena. In the paper by McEWEN [1948], the preliminary values of the diffusion coefficient referred to in the conclusion are too large and should be reduced to $\sim 2 \times 10^6$.

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ASSIMILATION OF HYDROCARBONS BY MICROORGANISMS*

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I. Introduction

A good many organisms, ranging in complexity from bacteria to man, absorb and assimilate certain hydrocarbons. Virtually all kinds and classes of hydrocarbons appear to be susceptible to attack by bacteria, yeasts, molds, or other allied microorganisms. The ability of microorganisms to attack hydrocarbons seems to be quite general rather than unique. This may prove to be true of higher animals also, but very little experimental evidence is available in face of the fact that hydrocarbons have been thought of as being biologically inert.

Besides being of importance in the metabolism of organisms, the assimilation of hydrocarbons is of considerable significance in nature and industry. The fact that hydrocarbons generally do not occur in deposits of decomposing plant and animal debris to the extent that they occur in living organisms (25,26,142) is *a priori* evidence that hydrocarbons are decomposed in all except peculiar environments, *e.g.*, source bed of petroleum, where conditions favor their preservation. Otherwise, the tendency would be for the earth's carbon to accumulate in hydrocarbons.

Petroleum or its products, in contact with water, may be modified by the action of hydrocarbon-oxidizing microorganisms (20,76,110, 158,186,195,197,215,226,227). Such organisms are believed to be responsible for the rapid disappearance of petroleum pollution in waterways (10,74), or wherever oil is spilled on water or soil (148,226). Hydrocarbon-oxidizing bacteria have been incriminated in the deterioration of both natural and synthetic rubber (127,160,163,232) and in the corrosion of underground pipelines and electrical conduits coated with paraffin-impregnated materials, elastomers, or other hydrocarbon products. The growth of hydrocarbon-oxidizing bacteria in aqueous medicinal or pharmaceutical preparations having hydrocarbon bases has resulted in discolored or otherwise altered products. Afflictions in human patients as well as other undesirable effects in cooling or cutting oils have been traced to the profuse growth of hydrocarbon-oxidizing bacteria (36,37,45,107,108).

On the positive side of the ledger are numerous proved or promising beneficial effects from hydrocarbon-oxidizing microorganisms such as, for example, the conversion of methane or higher hydrocarbons into useful organic acids or other products (174,179). Observations on hydrocarbon-oxidizing microorganisms suggest many applications in the discovery, recovery, and refining of petroleum (143,177,178, 180,196,228).

Dating from 1895 when Miyoshi (114) reported the attack of paraffin by *Botrytis cinerea*, more than one hundred species representing about forty genera of bacteria, yeasts, and molds have been shown by various workers to be able to utilize one or more kinds of hydrocarbons (76,128,148,189,226). Such microbes, which attack gaseous, liquid, and solid hydrocarbons of the aliphatic, olefinic, aromatic, and naphthenic series, have been shown to be quite widely distributed in nature. Besides a large number of pure hydrocarbons which have been investigated, various workers have demonstrated the microbial assimilation of crude oils, gasolines, lubricating oils, tars, asphalts, illuminating gases, natural and synthetic rubbers, paraffin waxes, petrolatums, mineral oils, petroleum ethers, and other mixtures of hydrocarbons.

Reviews of the scattered literature on the microbial assimilation of petroleum and its products have been prepared by Haas (66), Hessel (76), Osnitskaya (128), Tausson (189), and ZoBell (226).

II. Experimental Methods

A. MODIFICATION OF HYDROCARBONS

Commonest of the criteria for detecting the microbial utilization of liquid or solid hydrocarbons is their modification in media inoculated with the microorganisms in question. The pitting of paraffin wax, for example, or a decrease in the quantity of oil is indicative of utilization. The emulsification of various kinds of oil by microorganisms has been observed by numerous investigators (19,20,123,197,227). Likewise microorganisms may bring about color changes in oils or cause their complete disappearance (186). Tausson (188) followed the microbial decomposition of phenanthrene by noting the dissolution of crystals. Bacterial erosion of naphthalene crystals has also been observed (185).

Söhngen (158) observed the disappearance of as much as 7.5 mg. of crude oil per day per square decimeter of oil exposed to the culture. Tausz and Peter (197) noted changes in layers of crude oil 1 to 2 mm. thick after three days' incubation at 25°C., and within two weeks the oil had disappeared from the surface of the medium in which bacteria were growing. Wagner (215) reported the destruction of 1 g. of crude oil in eight days by *Bacterium benzoli* growing in 100 cc. of mineral solution enriched with oil.

B. MICROBIAL MULTIPLICATION

When microorganisms multiply in mineral salt solutions enriched with gaseous, liquid, or solid hydrocarbons as the sole source of energy and carbon, it is safe to assume that the hydrocarbon is utilized. Bacteria and yeasts may multiply in sufficient numbers to render hydrocarbon media turbid or they may form pellicles. Mold mycelia may appear throughout the medium or float in mats on the surface. Bacterial populations exceeding one billion per cubic centimeter have been detected in mineral media inoculated with soil and enriched with biphenyl, cetane, naphthalene, or other hydrocarbons (169,173).

Imelik (84) noted the multiplication of *Pseudomonas aeruginosa* in mineral medium enriched with heptane until at the end of 4 days' incubation there were 10^7 cells/cc., as compared with 10^8 cells/cc. of medium enriched with petroleum, 10^{12} cells/cc. in medium enriched with gasoline or glucose, and 10^{13} cells/cc. of medium enriched with petroleum jelly. Species of *Actinomyces*, *Sarcina*, and *Monilia* also multiplied in mineral medium enriched with petroleum or its products.

C. OXYGEN UPTAKE

Oxygen consumption by aerobes in mineral salt solutions containing hydrocarbons as the only oxidizable matter has been quite extensively employed as a criterion of hydrocarbon oxidation (60,78,234). The microbial oxidation of methane has been studied (72,82,101,118,180) by following changes in the volume and composition of the gas phase:

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O$$

By means of a siphon going to the bottom of a one-hole stoppered bottle containing inoculated mineral salt solution in an atmosphere of methane and oxygen, Söhngen (158) connected a cotton-plugged bottle containing sterile medium in such a way that any decrease in gas volume in the culture bottle resulted in the aspiration of sterile medium into the culture bottle. In this way gas consumption could be observed from day to day without interrupting the experiment. The technique has been adapted by other workers to the study of the microbial oxidation of various gaseous, liquid, and solid hydrocarbons. The volume of oxygen consumed always exceeds the volume of carbon dioxide produced.

Decreases in gas volume attributable to oxygen consumption resulting from the microbial oxidation of hydrocarbons have also been followed by manometric methods. Employing Warburg manometers, Stone *et al.* (169,170) found that light oils undergoing oxidation by mixed cultures gave respiratory quotients of around 0.63, as compared with a theoretical value of 0.67 for paraffin hydrocarbons, C_nH_{2n+2}, oxidized completely to carbon dioxide and water. The fermentation of heavy oils gave lower values, thereby indicating that there was less tendency for longer molecules of hydrocarbons to be oxidized completely to carbon dioxide and water than for shorter molecules.

Bacterial cultures investigated by Bushnell and Haas (19) gave R.Q. (respiratory quotient) values ranging from 0.30 to 0.70, with no apparent correlation between R.Q. and the nature of the hydrocarbon undergoing oxidation. The R.Q. of washed cells of *Bacterium aliphaticium*, as observed by Johnson *et al.* (97), averaged 0.47 for heptane, 0.48 for octane, 0.63 for nonane, and 0.63 for dodecane, as compared with 0.88 for glucose. The R.Q. for the bacterial oxidation of biphenyl (96) was 0.73, or 89% of the theoretical value for complete oxidation to carbon dioxide and water.

Oxygen consumption, in a glass-stoppered bottle filled to capacity with mineral solution enriched with hydrocarbon as the sole source of energy, has been used for studying the microbial oxidation of petroleum (77,234) and rubber (232) hydrocarbons. This B.O.D. technique, in which dissolved oxygen is determined by the Winkler method, has also been applied to estimating the abundance of hydrocarbon-oxidizing bacteria in sea water, sediment, and soil samples by the minimum dilution method.

D. METHYLENE BLUE REDUCTION

Tausz and Donath (196) reported the decoloration of methylene blue resulting from the action of *Bacterium aliphaticum liquefaciens* upon hexane. The reduction of methylene blue or similar redox indicators in mineral solutions enriched with hydrocarbons constitutes proof for the oxidation of the hydrocarbons, but there are a good many microorganisms which oxidize hydrocarbons without affecting the color of such indicators (226).

E. CARBON DIOXIDE PRODUCTION

Carbon dioxide seems to be the principal product resulting from the microbial oxidation of hydrocarbons (20,64,182,183,191,215). From 80 to 90% of the carbon in the hydrocarbons decomposed by the soil bacteria studied by Büttner (20) could be accounted for as carbon dioxide. According to data given by Söhngen (157), it is estimated that about half of the methane assimilated by *Methanomonas methanica* was oxidized to carbon dioxide and the other half was converted into bacterial cell substance and intermediate products. Söhngen (158) measured carbon dioxide production to indicate the relative rates of oxidation of paraffin oil and paraffin wax by various organisms.

The amount of carbon dioxide produced may be measured as such or its formation may be indicated by a decrease in the *p*H of the medium. Carbon dioxide plus organic acids formed by the microbial oxidation of hydrocarbons may decrease the *p*H of the medium from 0.2 to 2 units.

Sisler and ZoBell (154) measured carbon dioxide formation for following the microbial oxidation of naphthalene, anthracene, phenanthrene, 1,2-benzanthracene, 1,2,5,6-dibenzanthracene, and other carcinogenic hydrocarbons.

F. NITRATE AND SULFATE REDUCTION

A good many microorganisms reduce nitrate to nitrite in hydrocarbon media. Since it is easy to test for nitrate or nitrite, this is another useful criterion for the microbial utilization of hydrocarbons, although negative results are not infallible.

The same may be said regarding anaerobic sulfate-reducing bacteria, some strains of which assimilate certain hydrocarbons (125,139, 230,235), as indicated by hydrogen sulfide formation. The utilization of paraffin hydrocarbons higher than C_{10} by sulfate reducers was reported by Tausson and Aleshina (191), who postulated that heavy paraffins are thus converted into naphthenic or polymethylene hydrocarbons. Naphthalene, phenanthrene, and retene are attacked by sulfate reducers, according to Tausson and Vesselov (194).

The reduction of sulfates at the expense of hydrocarbons has also been reported by Schneegans (144). The rapid destruction of long-chain aliphatic hydrocarbons, various crude oils, kerosene, lubricating oil, and mineral oil by 27 different cultures of sulfate reducers was reported by Rosenfeld (139), who averred that hydrocarbon utilization by *Desulfovibrio* species is associated with the presence of a dehydrogenase system.

G. METHODS OF DISPERSING HYDROCARBONS IN MEDIUM

Since most hydrocarbons are only very slightly soluble in water, the rate at which they are attacked by microorganisms depends primarily upon the surface area exposed to enzymic action or the extent to which the hydrocarbons are dispersed in the medium. In general, liquid and solid hydrocarbons have been dispersed either by emulsification or absorption on the surface of sand, asbestos fibers, diatomaceous earth, glass wool, or other particulate material.

The growth of *Mycobacterium album*, *M. rubrum*, *Micrococcus paraffinae*, and other hydrocarbon-oxidizing bacteria was found by Söhngen (159) to be a function of soil surface. The addition of silicon dioxide or iron oxide stimulated petroleum oxidation. Kieselguhr or other particulate substances coated with paraffin wax provided for the activity of *Serratia marcescens* and other hydrocarbon-oxidizing bacteria observed by Greig-Smith (62). Tausson and Aleshina (191) mixed melted paraffin with powdered glass or kaolin to increase the free surface of paraffin. ZoBell (230) grew sulfate-reducing bacteria in plaster of paris prepared with mineral solution and paraffin oil or wax.

Heavy hydrocarbons may be liquefied by heating or dissolved in volatile solvents preparatory to dispersing them on the surfaces of solid particles. Emulsifying the hydrocarbons in aqueous media with a Waring Blendor and passing the mixture several times through a homogenizer has also yielded gratifying results. Stable emulsions of hydrocarbons, which are attacked by bacteria almost as fast as simple carbohydrates, have been prepared in this way by the author. When admissible, the use of a little gum acacia, gum arabic, or other stabilizing agent is recommended.

III. Occurrence of Hydrocarbon-Oxidizing Organisms

Microorganisms which attack methane, paraffin, or other hydrocarbons appear to be quite commonly present in soil. They are particularly abundant in oil-soaked soil around oil wells, refineries, leaky pipelines, gasoline pumps, etc. They also occur in swamps, lakes, river water, marine bottom deposits, petroleum separation tanks, sedimentation ponds in oil fields, and water bottoms of tanks in which petroleum or its products are stored.

The abundance of hydrocarbon-oxidizing bacteria in oil-soaked soil, petroleum sedimentation ponds, etc., is attributable partly to the development of adaptive enzymes which attack hydrocarbons. It has been observed by the author that many bacteria, yeasts, and molds which normally lack the ability to attack hydrocarbons develop this ability after prolonged cultivation on nutrient media in the presence of mineral oil.

The abundance or activity of methane-oxidizing bacteria in the surface soil overlayering subterranean deposits of petroleum is the basis of various geomicrobiological prospecting methods which have been proposed (15,115,143,177,178,180) but are still in the experimental stage. Methane oxidizers occur less abundantly in garden soil (1,55,72,73,101,119,158), sewage (54), and recent marine sediments (82). In this connection it is pointed out that only a few specialized species of bacteria attack methane and only with difficulty. The number of microbial species and the ease of utilization seem to increase with the chain length of paraffinic hydrocarbons, at least up to those in the range of C_{20} to C_{30}.

Paraffin-oxidizing microorganisms in soil have been described by Bushnell and Haas (19), Fleming (49), Gainey (53), Greig-Smith (62), Haag (64,65), Hopkins and Chibnall (79), Jensen (92–94), Rahn (133), Tausson and Aleshina (191), and Umbreit (205). Species of *Actinomyces*, *Aspergillus*, *Bacillus*, *Bacterium*, *Mycobacterium*, and *Penicillium* which attack paraffin were found in nearly all samples of soil, hay, leaves, manure, and peat examined by Büttner (20).

From 50,000 to 200,000 bacteria which utilized paraffin as a carbon and energy source were found per gram of garden soil by Söhngen (158). Up to 3000 paraffin-decomposing bacteria were detected per cubic centimeter of ditch water. Large numbers were also found in manure. Söhngen divided the paraffin oxidizers into two groups. The first group, which contained lipases, included *Bacterium fluorescens liquefaciens*, *B. pyocyaneum*, *B. lipolyticum* alpha, beta, gamma, and delta, *B. stutzeri*, and *Micrococcus paraffinae*. The second group, which attacked fatty acids but contained no lipase, included *Mycobacterium album*, *M. hyalinum*, *M. lacticola*, *M. luteum*, *M. phlei*, and *M. rubrum*.

Truffault and Bezssonoff (204) isolated bacteria from soil which oxidized paraffin oil, cyclohexane, and methylcyclohexane.

Nearly all of the stock cultures of *Pseudomonas* studied by Haas (66) grew in kerosene media, indicating that the ability to utilize hydrocarbons is a common characteristic of the genus. This also appears to be true of *Mycobacterium* (65,66,94,209) and *Actinomyces* (92,93) species. Vierling (209) isolated 23 strains of *Mycobacterium* from soil, which utilized benzene, petroleum, paraffin oil, and paraffin wax as the only source of carbon. *Mycobacterium lacticola*, isolated from soil by Birch-Hirschfeld (13), oxidized acetylene. Three species of *Actinomyces* and 14 strains of *Proactinomyces* studied by Umbreit (205) utilized paraffin.

Jensen (92) found that the abundance of *Proactinomyces* in soil was greatly increased by the addition of paraffin. Among the numerous organisms isolated from soil, which could utilize paraffin, were *Proactinomyces agrestis*, *P. actinomorphus*, *P. paraffinae*, *P. polychromogenes*, *P. minimus*, *Actinomyces albus*, and two other new species of *Actinomyces* designated "65" and "218W." Jensen (93) later described *Proactinomyces corallinus*, *P. salmonicolor*, and *P. opacus* as paraffin oxidizers. *P. ruber*, *P. polychromogenes*, *Actinomyces violacens-ruber*, *A. albus*, *A. madurae*, and *Penicillium notatum*, studied by Baldacci (6a), grew readily in mineral solution enriched with paraffin wax as the sole source of energy.

Ten species of *Micromonospora*, which utilized either paraffin wax, paraffin oil, or various aromatic hydrocarbons, were found in Wisconsin lake bottoms by Erikson (45). Sturm and Orlova (175) found paraffin-oxidizing bacteria in Ala-Kule Lake, Russia. From medicinal mud Goobin (58) isolated *Bacterium hidium* and other bacteria which attacked ethane, kerosene, and petroleum ether. Similar bacteria were detected in Dead Sea sediments by Elazari-Volcani (43). Hydrocarbon-oxidizing bacteria are commonly encountered in marine sediments (59,125,126,225,227,232,234). In investigating the use of mineral oils to control mosquito larvae, Headlee and Miller (74) found that the oil film on polluted water was broken by microorganisms which digest hydrocarbons.

A petroleum-oxidizing coccobacillus isolated from oil-well brine was believed by Lipman and Greenberg (109) to have come from a depth of 8700 feet. Ginsburg-Karagitscheva (56,57), Issatshenko *et al.* (88), Maliyantz (110), Wackenhut (214), and ZoBell (227) have recovered hydrocarbon-oxidizing bacteria from oil-well brines from various depths.

Isjurova (86) warned against the use of petrolatum or paraffin oil as sealing agents in B.O.D. tests because of the common occurrence of hydrocarbon-oxidizing bacteria in water and sewage.

IV. Action of Hydrocarbons on Microorganisms

A. ANTISEPTIC HYDROCARBONS

Although certain hydrocarbons are selective antiseptics, the rather common occurrence of bacteria and allied microorganisms associated with petroleum or its products is ample evidence that hydrocarbons are not germicidal for all organisms. Even toluene, which is sometimes employed as a preservative for enzyme preparations, is attacked in all concentrations by several species of bacteria and molds. Pickering (131) noted an increase in the organic content of soil following its treatment with benzene, paraffin oil, or ether, but it remained for later workers to prove that these substances are utilized by bacteria.

Soaking soil with toluene was found by Russell and Hutchinson (141) to cause a temporary decrease in the bacterial population followed by a marked increase. Similar results were observed by Buddin (17) in soil treated with toluene, benzene, cyclohexane, hexane, or pentane. The oxidation of toluene and other aromatic antiseptics by soil bacteria was established by Sen Gupta (151), who found further that phenol and cresol are also susceptible to microbial attack.

That certain soil bacteria can obtain their energy and carbon requirements from toluene, xylene, pseudocumene, mesitylene, naphthalene, cymene, pinene, hexane, benzene, chlorobenzenes, nitrobenzenes, and cresols was confirmed by Matthews (112). Toluene was oxidized by 25 species representing 7 genera of bacteria isolated from soil by Gray and Thornton (61). Naphthalene, phenol, or cresol was attacked by bacteria in 146 out of 245 soil samples examined.

Naphthalene, which is lethal for many microorganisms and which has been used as a soil "antiseptic," cannot be depended upon to sterlize soil. It actually promotes the growth of certain organisms (61,89,181). The addition of 1.28 g. of naphthalene to 100 g. of soil was observed by Jacobs (89) to result in an increase of the bacterial population from an initial count of a few million per gram to more than three billion per gram. Similar results were obtained by Tattersfield (181), who noted that whereas about 50 days were required for the disappearance of 50 mg. of naphthalene from 100 g. of soil initially treated, the second 50 mg. of naphthalene disappeared in 20 days and the third 50 mg. disappeared in 10 days.

Part of the increase in the bacterial population of soil treated with hydrocarbons is definitely due to their assimilation by bacteria and partly to a lethal action of the hydrocarbons on soil fauna, the dead bodies of which are oxidized by bacteria (89,112,181). Not only are aromatic hydrocarbons lethal for many forms; all paraffin oils studied by Marsland (111) from octane, C_8H_{18}, to tetradecane, $C_{14}H_{30}$, induced narcosis or death when applied to the surface of *Amoeba dubia*. According to Dawson and Belkin (30), *Amoeba proteus* was not injured by the injection of mineral oil.

Von Oettingen (212) rated octane as the most toxic of the saturated paraffinic hydrocarbons. Olefins are more toxic for animals than the corresponding saturated compounds, cycloparaffins are more toxic than olefins, and aromatic hydrocarbons are, in general, more toxic than homologous cycloparaffins. Toxicity generally increases with the number of side chains.

B. SELECTIVE ACTION OF HYDROCARBONS

The selective action of petroleum ether on enteric organisms is the basis of certain cultural methods for separating them (12,69,78,147, 216). Bierast (12) reported that *Escherichia coli* was killed by treatment with petroleum ether which injured neither typhoid nor paratyphoid bacilli. After confirming and extending these observations, Hall (69) proposed the addition of pentane to nutrient broth to inhibit *E. coli* and to promote the growth of *Eberthella typhi*. Heyn (78) and Schuscha (147) claimed success in detecting typhoid organisms in polluted water by treatment with petroleum ether. Walbum (216) failed to find any consistent difference in the susceptibility of different enteric organisms to petroleum ether, although there was a close relationship between the germicidal effect of 30 different petroleum fractions examined and their boiling points. In general, light ends were more germicidal than heavier hydrocarbons.

Baier (6) erroneously believed that the germicidal property of hydrocarbons is largely a function of their solubility in water. Jentsch (95) attributed the germicidal effect of illuminating gas to the presence of cyclic hydrocarbons, although it is now known that many microorganisms may tolerate high concentrations of benzene, toluene, or xylene and actually attack these compounds (45,61,112,151,189,215, 234). The antiseptic property of hydrocarbons was found by Van de Velde (207) to be roughly parallel to their oxidizability by potassium permanganate, mesitylene and xylenes being more effective antiseptics than benzene or toluene.

At this writing there seem to be too many unexplained peculiarities of microorganisms and their enzymes as well as unknown effects of experimental conditions to warrant any rigorous generalizations regarding what determines whether hydrocarbons will be harmful or beneficial. Certainly it is a dangerous and unwarranted assumption to consider either gaseous, liquid, or solid hydrocarbons to be biologically inert.

C. PRESERVATION OF CULTURES UNDER OIL

Covering microbial cultures with a layer of colorless mineral oil has been recommended as an effective way to preserve them for prolonged periods of time (14, 18,117,124,217). Delicate cultures of pneumococcus, meningococcus, gonococcus, streptococcus, and influenza bacilli, investigated by Birkhaug (14) and Parish (129), remained alive for several months in nutrient media overlayered with liquid paraffin. Details of the procedure for preserving bacterial cultures under paraffin oil and a review of the relevant literature are given by Morton and Pulaski (117).

Sherf (152) maintained cultures of *Alternaria*, *Fusarium*, and *Phytomonas* under mineral oil for several months. Buell and Weston (18) recommended the application of a layer of recently autoclaved heavy mineral oil about 1 cm. above the tip of agar slant cultures of fungi. The beneficial effect of the oil upon the prolonged survival of fungous cultures was attributed to: (*a*) the exclusion of oxygen with a resultant decrease in the metabolic activity of the fungi, (*b*) the retardation of dehydration of the medium, and (*c*) the exclusion of mites and other contaminating organisms. Edwards *et al.* (39) found that the oxygen consumption of fungous cultures was a function of the depth of overlayering oil.

The growth of fungi and bacteria on nutrient agar overlayered with oil was employed by Young (219) as a criterion of the oil's toxicity for vegetation. Toxicity of oils was found to increase with their sulfonatability. Hyaline, nearly unsulfonatable petroleum oils were useful for preserving cultures of bacteria and fungi. Mold mycelia and some bacteria grew through oil 1 to 5 mm. along the glass walls of culture receptacles. Tomkins (203) reported the penetration and utilization of vaseline by molds.

V. Microbial Oxidation of Gaseous Hydrocarbons

There seems to be more specificity in the ability of bacteria to attack gaseous hydrocarbons than higher homologs, probably because the latter have more vulnerable points and are thermodynamically less stable than short molecules. The greater oxidizability of higher homologs, however, is partly offset by their decreasing solubility with increasing complexity.

In order to account for the low incidence of methane in the atmosphere in spite of its abundant formation in swamps, soil, etc., Urbain (206) postulated that it was either oxidized by ozone in the atmosphere or in the presence of green plants, probably by bacteria. Then almost simultaneously Kaserer (101) and Söhngen (156) proved the bacterial oxidation of methane.

The physiology and ecology of methane-oxidizing bacteria have been studied by Söhngen (157,158), Störmer (171), Giglioli and Masoni (54,55), Harrison and Aiyer (72), Münz (118,119), Aiyer (1), Hasemann (73), Yurovskii *et al.* (220), Wiken (218), Hutton (82), Slavnina (155a,b), and many others. However, owing to technical difficulties encountered in studying them and a lack of sustained interest in methane-oxidizing bacteria, information is still woefully scant on their toxanomic position and physiology.

Although most workers credit *Methanomonas methanica* as being the principal, if not the only, species to oxidize methane, there is some evidence that other bacteria utilize methane. *Pseudomonas fluorescens* was identified by Aiyer (1) as the bacterium responsible for the oxidation of methane in swamp paddy soil. Hutton (82) recorded that a species of *Methanomas* quite unlike *M. methanica*, as well as certain strains of *Pseudomonas fluorescens*, utilized methane. The methane-oxidizing cultures of Münz (119) frequently contained *P. fluorescens* and/or *P. aeruginosa*, but, since pure cultures of neither could utilize methane, he concluded that they grew at the expense of the organic matter synthesized by methane bacteria. Münz regarded it as doubtful whether the species of methane bacteria with which he worked was the same species described by earlier workers (101,156).

There is disagreement among investigators and a general lack of data as to whether *Methanomonas methanica* can also utilize higher hydrocarbons. The methane oxidizer studied by Münz (118) was said to utilize neither ethane nor ethylene, but the "methane bacterium" of Tausz and Donath (196) oxidized hydrogen, ethane, propane, butane, and higher paraffin hydrocarbons as well as methane, which may cause one to wonder if their culture was pure. Certain methane oxidizers believed by Hutton (82) to be pure cultures were found to assimilate ethane and propane. Be this as it may, it is generally easier to demonstrate the oxidation of ethane and higher hydrocarbons than methane by mixed cultures of soil bacteria in spite of the more common occurrence of methane.

A strain of *M. methanica*, studied by Slavnina (155b), utilized methane, ethane, and propane. All except 8 out of 342 cultures of methane-oxidizing bacteria isolated from oil fields by Slavnina (155a) gave a positive test for peroxidase, as indicated by a blue color when treated with guaiacol and hydrogen peroxide.

The so-called geomicrobiological prospecting methods of Blau (15), Mogilevskii (115), Sanderson (143), Taggart (177,178,180), and others are based upon the presence or activities of bacteria which oxidize gaseous hydrocarbons in surface soil overlayering subterranean deposits of petroleum. Geochemical methods must take into consideration the rapidity with which bacteria may oxidize hydrocarbons in soil samples during their transportation and storage (115,235).

The catalytic or chemical oxidation of methane generally results in the formation of methyl alcohol, formaldehyde, formic acid, and carbon dioxide, in the order named, although hydrogen, carbon, carbon monoxide, alcohols, aldehydes, acetone, acids, saturated and unsaturated hydrocarbons, resins, and other products may be formed, depending upon the conditions (40). No sustained effort has been made to detect any of these products except carbon dioxide in cultures of methane-oxidizing bacteria and the same must be said regarding the utilization of the theoretical intermediate products of oxidation.

Bacterium hidium, isolated from medicinal mud by Goobin (58), oxidized kerosene and ethane, but no mention was made of its ability to attack methane or other gaseous hydrocarbons. Acetylene but not ethylene, propylene, or methane provided the energy and carbon requirements for the growth of *Mycobacterium lacticola* (13). Ethylene stimulated the respiration of *Aspergillus fumigatus*, *A. flavus*, and *A. niger*, although a high concentration of ethylene retarded the growth of these molds (208).

In their review of the fragmentary literature on the microbial oxidation of gaseous hydrocarbons, Egloff and Schaad (40) pointed out the need of investigations on the action of bacteria on ethane, propane, butanes, 2,2-dimethylpropane and allied compounds.

VI. Relative Oxidizability of Different Classes of Hydrocarbons

A. ALIPHATIC *VS.* AROMATIC COMPOUNDS

A few generalizations regarding the relative oxidizability of different classes of hydrocarbons seem to be warranted, after discounting differences attributable either to the specificity of hydrocarbonoclastic enzymes of various microorganisms or to the degree of dispersion or solubility of hydrocarbons in the nutrient medium. In general, aliphatic or paraffinic hydrocarbons are attacked more rapidly and by more microbial species than aromatic compounds. It is a commonly reported observation that organisms which assimilate aromatic or naphthenic hydrocarbons attack the corresponding aliphatic compound more readily, and there are many reports of the inability of aliphatic hydrocarbon oxidizers to attack cyclic compounds; for example, neither benzene nor xylene was attacked by *Actinomyces oligocarbophilus* (105), which assimilated aliphatic hydrocarbons.

Petroleum fractions high in paraffinic hydrocarbons were reported by Stone *et al.* (170) to be more readily assimilated by soil microorganisms than those of high aromatic content, while the naphthenic fractions occupied an intermediate position.

After noting that *Bacterium aliphaticum* quantitatively decomposed aliphatic hydrocarbons ranging from C_6H_{14} to $C_{34}H_{70}$ but failed to attack benzene, toluene, xylene, or other aromatic or naphthenic hydrocarbons, Tausz and Peter (197) suggested that such bacteria be employed for freeing cyclic hydrocarbons from aliphatic compounds. When grown in mixtures of hydrocarbons, *Bacterium aliphaticum liquefaciens* quantitatively decomposed both aliphatic and naphthenic hydrocarbons and left all aromatic hydrocarbons unaltered. Among the naphthenic hydrocarbons shown to be attacked by this organism were cyclohexane, methylcyclohexane, 1,3-dimethylcyclohexane and 1,3,4-trimethylcyclohexane (197).

After observing that *Pseudomonas fluorescens* and *Bacterium aliphaticum* readily attacked higher aliphatic hydrocarbons but not benzene, toluene, xylene, or short-chain aliphatic hydrocarbons, Johnson *et al.* (97) pondered whether hydrocarbons which are powerful fat solvents may be less readily assimilated than those which are less likely to dissolve cell lipides.

Whether the greater susceptibility of aliphatic hydrocarbons to microbial attack is attributable to physical properties or chemical configuration is not known, but aromatic hydrocarbons are attacked by a good many microorganisms. *Bacillus hexacarbovorum* (171), *Bacterium benzoli* (124), and *Bacillus toluolicum* (189) assimilated benzene, toluene, and xylene in concentrations up to one part in 10,000 of mineral media. The occurrence in soil of bacteria which decompose benzene, toluene, naphthalene, or other aromatic compounds has been reported by Gray and Thornton (61), Jacobs (89), Matthews (112), Sen Gupta (151), Tattersfield (181), and Wackenhut (214).

From oil-soaked soil Tausson isolated *Bacterium naphthalinicus*, *Bacillus naphthalinicus liquefaciens*, and *B. naphthalinicus non-liquefaciens* which assimilated naphthalene (181) and *B. phenanthrenicus bakiensis* and *B. phenanthrenicus guricus* which assimilated phenanthrene (188). ZoBell *et al.* (234) isolated from marine sediments bacteria which oxidized benzene, toluene, xylene, naphthalene, and anthracene, though none as readily as paraffinic hydrocarbons of comparable molecular weight. Several species of *Micromonospora* isolated from lake mud by Erikson (45) oxidized toluene and naphthalene.

Enrichment cultures of soil bacteria studied by Strawinski and Stone (173) attacked naphthalene, biphenyl, tetralin, decalin, and butylbenzene, but not nearly as readily as aliphatic hydrocarbons. The ability of anaerobic sulfate reducers to assimilate hydrocarbons is restricted primarily to aliphatic compounds (125,139), although aromatic hydrocarbons are slowly attacked by certain strains (194,227, 235).

B. EFFECT OF CHAIN LENGTH ON OXIDIZABILITY OF HYDROCARBONS

As a rule long-chain hydrocarbons are attacked more readily and by more microbial species than those of low molecular weight. When similarly dispersed throughout the medium to compensate for differences in solubility, the susceptibility of petroleum products to microbial oxidation generally increases with the melting or boiling point. Mixed microflora from soil or sediments ordinarily attack petroleum ether more readily than natural gas, and oxidized with increasing ease are gasoline, kerosene, lubricating oil, and paraffin wax, in the order named (19,68,97,158,234).

Several *Mycobacterium* species observed by Haas *et al.* (68) grew on paraffin wax much better than on gasoline or kerosene. Most of the *Pseudomonas* species also grew better on paraffin wax and oils than on kerosene and better on kerosene than on gasoline, although one *Pseudomonas* species grew on petroleum ether, gasoline, and kerosene but on neither paraffin wax nor oil.

Most of the 16 species of *Mycobacterium* and *Pseudomonas* isolated from soil and ditch water by Söhngen (158) assimilated hydrocarbons having boiling points higher than 150°C. but not those with lower boiling points. *Micrococcus paraffinae*, like *Mycobacterium album*, *M. rubrum*, *Pseudomonas fluorescens*, and certain raw cultures, rapidly oxidized finely divided paraffin wax, but all grew less readily on pentane, hexane, heptane, and octane than on higher members of the series. These organisms failed to attack hydrocarbons having fewer than five carbon atoms per molecule.

Cultures of *Bacterium aliphaticum* and *B. aliphaticum liquefaciens* attacked all aliphatic hydrocarbons tested ranging from pentane, C_5H_{12}, to tetratriacontane, $C_{34}H_{70}$, but no hydrocarbon lower than pentane was attacked by either organism (195,197). Unlike other investigators (82,118), who have found a high degree of specificity in the ability of methane oxidizers to oxidize only methane, Tausz and Donath (196) reported that their "methane bacterium" also utilized ethane, propane, butane, pentane, hexane, and higher hydrocarbons with increasing ease. The "paraffin bacterium" of Tausz and Peter (197), probably a *Pseudomonas*, attacked no aliphatic hydrocarbon lower than hexadecane, $C_{16}H_{34}$, but it attacked with increasing ease higher members of the paraffin series.

In the hands of Johnson *et al.* (97), *Bacterium aliphaticum* and *Pseudomonas fluorescens* grew with increasing ease on gasoline, kerosene, lubricating oil, and paraffin oil. *P. fluorescens* grew on no pure hydrocarbon of shorter chain length than dodecane, $C_{12}H_{26}$, but *B. aliphaticum* grew better on hexane, heptane, octane, and nonane than on dodecane.

Strawinski's (172) observations on the action of mixed soil microflora on 24 different hydrocarbons indicated that the longer the aliphatic portion of either paraffinic or mononuclear aromatic compounds, the more readily they are dissimilated. Hexadecane was oxidized more readily than any other compound tested. The observation of Stone *et al.* (169) that medium-weight petroleum fractions are more susceptible to microbial attack than the heavier fractions may be attributable to the chain length of the hydrocarbons, the kinds of hydrocarbons present in the various fractions, or the degree of dispersion of the hydrocarbons in the mineral medium. Rahn (133) reported that soil fungi grew better on paraffin wax having a melting point of 45° than on that melting at 56°C. Similarly, Hopkins and Chibnall (79) noted that *Aspergillus versicolor* showed good growth on *n*-tricosane, $C_{23}H_{48}$, fair growth on *n*-heptacosane, $C_{27}H_{56}$, *n*-nonacosane, $C_{26}H_{60}$, and *n*-triacontane, $C_{30}H_{62}$, slight growth on *n*-tetratriacontane, $C_{34}H_{70}$, and no growth on *n*-pentatriacontane, $C_{35}H_{72}$.

According to Tausson and Aleshina (191), anaerobic sulfate-reducing bacteria can utilize no paraffinic molecule smaller than decane. Confirming this assertion, which was based upon theoretical thermodynamic considerations, Novelli and ZoBell (126) actually observed the utilization by sulfate reducers with increasing ease of decane, $C_{10}H_{22}$, tetradecane, $C_{14}H_{30}$, eicosane, $C_{20}H_{42}$, docosane, $C_{22}H_{46}$, and hentriacontane, $C_{31}H_{64}$.

C. EFFECT OF UNSATURATION OR DOUBLE BONDS

Hydrocarbons having double bonds seem to be more susceptible to microbial oxidation than their saturated counterparts. Haag (65) came to this conclusion after observing that *Mycobacterium* species utilized pentene, C_5H_{10}, but not pentane, C_5H_{12}, and mixtures of hydrocarbons having high iodine numbers. For example, carbon dioxide was produced from the oxidation of a paraffin having an iodine number of 4.6 at an average rate of 103 mg. per week as compared with 32 mg. of carbon dioxide per week from a paraffin having an iodine number of 2.4. Seven other paraffins having intermediate iodine numbers were oxidized at intermediate rates corresponding to their degrees of unsaturation.

When lubricating oils were subjected to the action of bacteria, a decrease in the iodine number suggested to Tausson and Shapiro (192) that unsaturated hydrocarbons are preferentially attacked.

Desulfovibrio species were found by ZoBell *et al.* (235) to oxidize hexadecene, $C_{16}H_{32}$, appreciably faster than its saturated homolog, hexadecane, $C_{16}H_{34}$. Butadiene, $CH_2{=}CH{-}CH{=}CH_2$, isoprene or methylbutadiene, $CH_2{=}CH{-}C(CH_3){=}CH_2$, isobutylene, $(CH_3)_2C{=}CH_2$, styrene, $C_6H_5{-}CH{=}CH_2$, and allied unsaturated "rubber" hydrocarbons have been shown to be very vulnerable to microbial attack (23).

Although the methane bacteria investigated by Münz (118) failed to attack ethylene, unidentified species in mixed cultures formed films or pellicles on the surface of water through which ethylene was bubbled. The "methane bacterium" of Tausz and Donath (196) utilized ethylene, propylene, and butylene more readily than methane or ethane.

Two different cultures studied by Tausz and Peter (197) grew better on octene, C_8H_{16}, than on octane, C_8H_{18}, an observation which has been confirmed by Strawinski (172) with mixed cultures of soil bacteria. The position of the double bond may also influence the results as indicated by the fact that *n*-pentene, $CH_2{=}CHCH_2CH_2CH_3$, supported the growth of mixed cultures of soil bacteria much better than pentene-2, $CH_3CH{=}CHCH_2CH_3$ (172).

In the cyclic series there seems to be no consistent relationship between the presence of double bonds and the oxidizability of hydrocarbons by microorganisms. Naphthalene, which has five double bonds, was utilized more readily by soil bacteria than its completely saturated counterpart, decalin, but, conversely, benzene, which has three double bonds, was utilized less readily than its completely saturated counterpart, cyclohexane (172).

Two enrichment cultures of marine bacteria which oxidized ethane, $H_3C{-}CH_3$, were found to utilize ethylene, $H_2C{=}CH_2$, more rapidly, and they attacked acetylene, $HC{\equiv}CH$, more rapidly, than either ethane or ethylene (235). The susceptibility of such unsaturated compounds to microbial attack may help to account for the general absence of olefinic hydrocarbons in petroleum. In this connection it is of interest to point out that certain hydrogenase-producing anaerobes have been observed to activate the hydrogenation or saturation of octene and hexadecene.

D. EFFECT OF BRANCHING OR SIDE CHAINS

Although there are many exceptions to the rule due to unpredictable enzyme specificity of hydrocarbonoclastic microorganisms, in general *iso* or branched-chain hydrocarbons are more susceptible to microbial oxidation than normal or straight-chain compounds. For example, isooctane or 2,2,4-trimethylpentane, $CH_3C(CH_3)_2CH_2CH(CH_3)CH_3$, was utilized much more rapidly than *n*-octane, $CH_3(CH_2)_6CH_3$, by mixed cultures of soil (172) and marine (223,235) bacteria, although the reverse relationship has been reported for certain organisms (97,173).

The growth of *Bacterium aliphaticum liquefaciens* was supported by cetylbenzene, $C_6H_5C_{16}H_{33}$, but not by either benzene, C_6H_6, or toluene, $C_6H_5CH_3$ (196). This same organism oxidized dimethylcyclohexane, $C_6H_{10}(CH_3)_2$, and trimethylcyclohexane, $C_6H_9(CH_3)_3$, more rapidly than cyclohexane, C_6H_{12} (197).

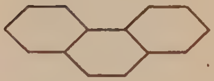
Matthews (112) claimed that the introduction of a methyl group into the benzene ring rendered the resulting compound more susceptible to bacterial oxidation because of the greater potential energy, ΔH, of the methylated compound. Thus toluene, $C_6H_5CH_3$, was found to cause a greater increase in the bacterial population when added to soil than benzene, xylene, $C_6H_4(CH_3)_2$, greater than toluene, and mesitylene, $C_6H_3(CH_3)_3$, greater than xylene. Similarly, Wagner (215) found that *Bacterium benzoli* utilized either toluene or xylene more readily than benzene. Soil bacteria studied by Strawinski and Stone (173) grew fairly well on butylbenzene, $C_6H_5C_4H_9$, but not at all on either benzene or toluene. Mixed microflora from soil utilized toluene more readily than benzene or *m*-xylene (186). One of the four strains of *Bacillus toluolicum* observed by Tausson (188) utilized ethylbenzene, $C_6H_5C_2H_5$, and toluene more readily than benzene, but the reverse relationship was found for the other three strains. Pseudocumene, cumene, and *p*-thymol were attacked only very slowly by *B. toluolicum.*

The addition of a methyl group to naphthalene was found by Strawinski (172) to reduce the availability of the resultant compound to microbial attack by soil bacteria.

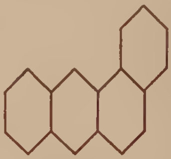
E. POLYCYCLIC HYDROCARBONS

Most investigators have found that naphthalene is dissimilated more readily and by more microbial species than benzene, but only fragmentary data are available on the microbial oxidizability of anthracene and more complex hydrocarbons having condensed benzene nuclei. When added to soil, naphthalene generally causes a greater increase in the bacterial population than benzene (61,89,109,112,181). Strawinski and Stone (173) found no bacteria in soil enrichment cultures which were capable of growing on benzene, although both naphthalene and biphenyl supported large bacterial populations.

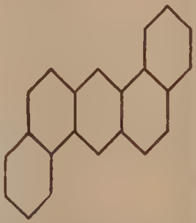
According to Tausson (186,189), naphthalene, biphenyl, anthracene, and phenanthrene are readily utilized by many soil bacteria. Certain sulfate-reducing bacteria (194) slowly attacked naphthalene, phenanthrene, and retene (7-isopropyl-1-methylphenanthrene). Tausson described three new species which assimilated naphthalene (185) and two which assimilated phenanthrene (188). From Maikopsy soils Tausson obtained cultures which oxidized acenaphthene, anthracene, bibenzyl, biphenyl, diphenylmethane, fluorene, and stilbene. Sisler and ZoBell (154) noted that phenanthrene and anthracene were assimilated by marine bacteria somewhat faster than either naphthalene or 1,2-benzanthracene, but 1,2,5,6-dibenzanthracene was assimilated only about one fourth as fast.



Phenanthrene



1,2-Benzanthracene



1,2,5,6-Dibenzanthracene

From oil-field soils Osnitskaya (128) cultivated mixed microflora which utilized naphthenic acids as the sole source of carbon. The destruction of naphthenic acids was accompanied by an increase in the iodine number and a decrease in the acid number. *Pseudomonas oleovorans* and large numbers of other bacteria found growing in cutting oils were believed by Lee and Chandler (107) to live on naphthenic acids in the oils.

VII. Action of Microorganisms on Hydrocarbon Derivatives

The decomposition of phenol and *o*-, *m*-, and *p*-cresol by soil bacteria was first demonstrated by Störmer (171) in 1907. Six years later Perrier (130) described several species of *Penicillium*, *Mucor*, *Torula*, yeasts, and bacteria, including four varieties of *Bacillus benzoicus*, which decomposed phenol, salicylic acid, and benzoate as the sole source of carbon and energy.

From sewage Fowler *et al.* (50) isolated *Flavobacterium helvolus*, which destroyed 0.1% phenol in mineral medium. Kalabina and Rogovskaya (99) studied sewage bacteria which utilized phenol in concentrations as high as 0.3%. Other phenol-oxidizing bacteria have been found in soil (9,29,47,61,151,155,210), lake mud (45), effluent from a coke-benzene plant (41,42), and in marine sediments (235).

Most of the ten strains of *Micromonospora*, which Erikson (45) isolated from lake mud, assimilated phenol, *m*-cresol, β-naphthol, resorcinol, trinitroresorcinol, picric acid, and *p*-dichlorobenzene, as well as toluene and naphthalene. Moore (116) observed *Proactinomyces* species from soil which utilized pyridine, aniline, nitrobenzene, and phenol as the sole source of energy.

Buddin (17) noted a great increase in the bacterial population of soil treated with phenol, cresol, quinone, hydroquinone, and pyridine, as well as with certain paraffinic, aromatic, or naphthenic hydrocarbons, but it remained for Matthews (112) to prove that these substances were oxidized by bacteria. Matthews also demonstrated the microbial utilization of chlorobenzenes and nitrobenzenes. Gray and Thornton (60,61) described several species of soil bacteria which could oxidize phenol, cresol, resorcinol, phloroglucinol, toluene, or naphthalene.

Phenol was decomposed by five different strains of *Achromobacter* species studied by Czekalowski and Skarzynski (29,155). Utilized in the order of decreasing ease by one strain of *Achromobacter* were hydroxybenzoate, dihydroxybenzoate, benzoate, phenyl acetate, phenyl benzoate, *o*-cresol, diphenylacetate, benzyl alcohol, *o*-aminobenzoate, phenol, phenyl sulfate, orcinol, *m*-cresol, *p*-cresol, *o*-aminobenzoate, pyrogallol, benzamide, cyclohexanol, and *m*-dihydroxybenzene. Not attacked were several closely related aromatic compounds, including *p*-dihydroxybenzene, nitrobenzene, aminobenzene, benzil, naphthol, and phthalic acid. The specificity of the attack is illustrated by the fact that 3,4-xylenol-1-ol was readily utilized but 3,5-xylenol-1-ol was not attacked; *o*-diphenol (catechol) was readily utilized but *p*-diphenol (hydroquinone) was not attacked by the *Achromobacter* strain. The highly specific enzyme system responsible for the breakdown of aromatic compounds was believed to contain esterases.

Benzoate was utilized by nearly all strains of *Pseudomonas* examined by Stanier (165), but phenol was utilized by only three out of 22 strains tested. Only one strain attacked *o*- and *m*-hydroxybenzoate, while 21 strains attacked *p*-hydroxybenzoate. Benzaldehyde was attacked by 20 strains, benzyl alcohol by 17, and phenyl acetate by 14 strains. The attack of all such aromatic compounds was believed to be brought about by highly specific adaptive enzymes.

Three species of phenanthrene-decomposing bacteria, *Bacillus phenanthrenicus bakiensis*, *B. phenanthrenicus guricus*, and *Bacterium phenanthrenicum*, were found by Tausson (188) to attack saligenin, *o*-salicylic acid, *o*-hydroxybenzaldehyde, pyrocatechol, and quinic acid. Two species utilized hydroquinone and one species utilized phenol. Resorcinol, phloroglucinol, pyrogallol, and phthalic acid were not attacked.

VIII. Products of Hydrocarbon Oxidation

Very little is known regarding the mechanism by which hydrocarbons are attacked by microorganisms. It is generally agreed, however, that carbon dioxide and cell substance are the principal products resulting from the microbial dissimilation of hydrocarbons. Organic acids, ketones, alcohols, aldehydes, and modified hydrocarbons have also been detected as intermediate or end products.

A. CELL SUBSTANCE

An appreciable percentage of the hydrocarbon dissimilated by microorganisms may be converted into microbial protoplasm or cell substance, particularly during the early stages of incubation. From the number and mass of bacteria developing in mineral media enriched with hydrocarbons as the sole source of carbon, ZoBell (226,235) estimated that from 25 to 35% of the carbon content of paraffinic hydrocarbons appeared as bacterial protoplasm. Comparable findings for mold fungi have been reported by Tausson (187), who reported results in terms of an "economic coefficient":

$$E = \frac{\text{(weight of mold mycelium)}}{\text{(weight of HC utilized)}} \times 100$$

The economic coefficient resulting from the growth of *Aspergillus flavus* on paraffin wax ranged from 52.3 to 92.5, the highest values being found during the early stages of incubation. These values may be compared with economic coefficients of 35.1 to 39.2 for beeswax and 26 to 28 for glucose.

The amount of organic matter, probably cell substance, produced by methane-oxidizing bacteria was determined by Söhngen (156,157) and Münz (118,119) as a criterion of activity. Aiyer and associates (1,72) like Giglioli and Masoni (54,55) considered organic matter formation one of the most important functions of methane oxidizers in soil. Harper (71) noted a marked increase in the organic content of soil around leaky gas mains, presumably due to the bacterial oxidation of methane and other hydrocarbons. Schollenberger (145) also observed increased biological activity in soil resulting from leaking natural gas.

B. CARBON DIOXIDE

Söhngen (158) observed the development of bacteria and the formation of insignificant quantities of organic acids during the dissimilation of higher paraffins, but the principal products were carbon dioxide and water. Tausz and Peter (197) came to the same conclusion after comparing the quantity of carbon dioxide produced with the amount of oxygen consumed by bacteria decomposing hydrocarbons. The relatively high R.Q. values observed by others (19,96,97,169,170) for the oxidation of hydrocarbons have already been mentioned.

Although Wagner (215) obtained indirect evidence for the formation of hydroquinone and various organic acids, carbon dioxide was the principal product resulting from the oxidation of benzene and toluene by *Bacterium benzoli*.

Büttner (20) accounted for from 80 to 90% of the carbon in paraffin dissimilated by soil microbes as carbon dioxide, the remainder appearing as cell substance, fatty acids, and lesser quantities of other intermediate products. His values, however, for the amount of cell substance formed are probably too low because in determining the former, Büttner extracted the cultures with carbon tetrachloride which could be expected to dissolve cell lipides and other products besides paraffin wax. The acid-fast bacteria with which he was working might have contained appreciable quantities of lipides.

Approaching the problem from the viewpoint of the biological purification of sewage and other waste waters, Isjurova (87) showed that in the presence of appropriate nutrients and oxygen various kinds of hydrocarbons were almost quantitatively oxidized to carbon dioxide and water.

C. ORGANIC ACIDS

Tausson (186,187) questioned the formation of free fatty acids by *Aspergillus flavus* because of the ease with which such products are attacked by the mold, and, moreover, he observed no increase in acidity of mineral medium in which paraffin was being decomposed. Nonacidic products detected in appreciable amounts in cultures of fungi growing on paraffin wax were assumed by Tausson (183,184) to consist in part of esters of fatty acids and higher alcohols.

Increases in the saponification number and the emulsification of crude oil undergoing microbial decomposition were attributed by Tausson and Shapiro (192) to the formation of fatty and naphthenic acids. The emulsification of the unfermented part of the oil and the decrease in the *p*H of the medium also indicated to Bushnell and Haas (19) and to Stone *et al.* (170) that paraffinic hydrocarbons were dissimilated with the formation of long-chain fatty acids.

According to Strawinski (172), the bacterial oxidation of cetane and naphthalene resulted in a more acid reaction than could be accounted for upon a basis of the amount of carbonic acid produced. Significant quantities of *o*-salicylic acid were detected in naphthalene cultures of *Pseudomonas aeruginosa*. Soil bacteria studied by Jacobs (89) formed phthalic acid from naphthalene.

T. A. Tausson (182) claimed that fatty acids and carbon dioxide were produced from paraffin by certain yeasts. The microbial formation of traces of acetic and lactic acids from kerosene was reported by Thaysen (200). A patent issued to Taggart (179) disclosed a bacterial method for converting gaseous paraffinic hydrocarbons into waxy acids, low boiling point alcohols, and esters.

Haas *et al.* (68) isolated small quantities of organic acids, having melting points ranging from 25 to 30°C., from bacterial cultures growing on mineral oil. Acid formation by *Pseudomonas aeruginosa* from petroleum, heptane, gasoline, and petroleum jelly was observed by Imelik (84). Formic and valeric acids were identified in cultures growing on cyclohexane (85).

The oxidation of benzene to muconic acid in experimental animals has been reported (11,90,122,201). There is also evidence that animals oxidize toluene to benzoic acid (213). Stetten (168) administered hexadecane tagged with heavy hydrogen to prove that rats can oxidize this hydrocarbon to fatty acids.

D. ALDEHYDES

Imelik (85) detected formaldehyde in cultures of *P. aeruginosa* assimilating cyclohexane. The formation of aldehydes by *Pseudomonas* species dissimilating naphthalene was suspected by Strawinski (172). Acetaldehyde has been reported as an intermediate product in the microbial oxidation of kerosene (200) and acetylene (13).

E. ALCOHOLS AND OXYPHENOLS

A volatile alcohol, thought to be isopropanol, as well as glycol and glycerol were produced from paraffin oil by soil microflora observed by Haas (66). Molds growing in mineral oil medium produced small amounts of ergosterol and cholesterol, but no sterols were found in bacterial cultures acting on oil (68). Certain fungi studied by Tausson (184) were believed to form higher alcohols during the dissimilation of paraffin wax.

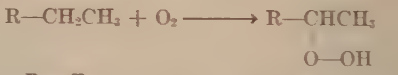
In an effort to learn how higher paraffins are oxidized by molds, Hopkins and Chibnall (79) experimented with oxygenated derivatives of the hydrocarbons. Ketone derivatives, such as 14-heptacosanone $CH_3(CH_2)_{12}CO(CH_2)_{12}CH_3$, and 16-hentriacontanone, $CH_3(CH_2)_{14}CO$-$(CH_2)_{14}CH_3$, were utilized more readily than the corresponding hydrocarbons, *n*-heptacosane, $C_{27}H_{56}$, and hentriacontane, $C_{31}H_{64}$, but the secondary alcohols, 14-heptacosanol, $CH_3(CH_2)_{12}CHOH(CH_2)_{12}CH_3$, and 16-hentriacontanol, $CH_3(CH_2)_{14}CHOH(CH_2)_{14}CH_3$, were not utilized. From such experiments it was concluded that the primary products of oxidation of paraffinic hydrocarbons are ketones or possibly polyketones which are oxidized further to shorter fatty acids and then to carbon dioxide as fast as formed. The intermediate formation of alcohols or esters, of fatty acids and alcohols was questioned, although there is ample evidence that hydroxy compounds, including phenols, are readily attacked by many microorganisms. As a matter of fact, the oxidizability of compounds seems to increase with an increase in the number of carbon atoms which are linked with hydroxy, carboxy, or keto groups (128).

After observing that cyclohexanol was dissimilated by *Pseudomonas aeruginosa* in the same fashion as cyclohexane, Imelik (85) postulated that the former was an intermediate product in the oxidation of the latter:

$$C_6H_{12} + \tfrac{1}{2}\,O_2 \longrightarrow C_6H_{11}OH$$

$$C_6H_{11}OH + 2\,O_2 \longrightarrow C_4H_9COOH + HCOOH$$

Also considered as intermediate products were peroxides, which increased progressively in amount during the first five days of incubation and then gradually disappeared. The initial intermediate products in the chemical oxidation of hydrocarbons are thought (236) to be hydroperoxides:

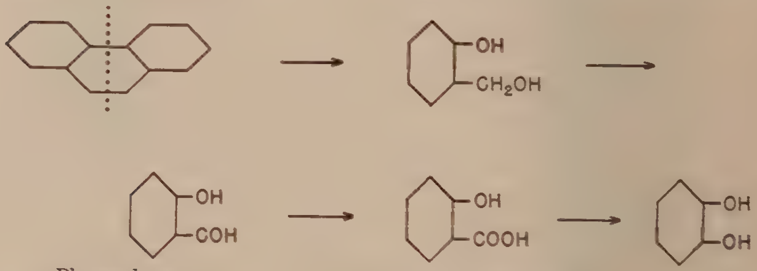


$$\underset{\text{Paraffin}}{R\!-\!CH_2CH_3} + O_2 \longrightarrow \underset{\text{Hydroperoxide}}{R\!-\!\underset{\displaystyle O\!-\!OH}{\underset{|}{C}}HCH_3}$$

Paraffin Hydroperoxide

The hydroperoxides are then further oxidized to aldehydes, ketones, organic acids, and carbon dioxide (236).

Upon a basis of the rapidity with which three species of phenanthrene-oxidizing bacteria assimilated the intermediate compounds in question, Tausson (188) postulated the stepwise dissimilation as follows:

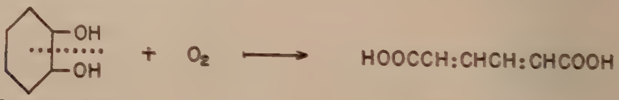


Phenanthrene
o-Hydroxybenzaldehyde

o-Hydroxybenzyl alcohol
o-Salicylic acid

Pyrocatechol

The benzene nucleus of pyrocatechol, or possibly of salicylic acid—both of which were readily attacked by the bacteria—was believed to be split with the formation of muconic acid, which is then rapidly oxidized to carbon dioxide:



Pyrocatechol Muconic acid

The inability of the bacteria to utilize any of the following closely related compounds indicated to Tausson that none of them is an intermediate product in the oxidation of phenanthrene because the latter was oxidized completely to carbon dioxide and water: resorcinol, phloroglucinol, pyrogallol, and phthalic acid.

Judging from the observed inability of *Bacterium naphthalinicum* and two other allied naphthalene-decomposing bacteria to attack pyrocatechol, resorcinol, phloroglucinol, pyrogallol, phthalic acid, α-naphthol, or β-naphthol, Tausson (185) concluded that none of these compounds could be intermediate products in the dissimilation of naphthalene. He postulated, but failed to prove, that both benzene rings in the naphthalene molecule are ruptured simultaneously by bacteria. As has already been pointed out, however, certain bacteria have been demonstrated to produce *o*-salicylic acid (172) and phthalic acid (89) from the dissimilation of naphthalene, which again emphasizes differences attributable to enzyme specificity or to experimental conditions.

Unlike the anaerobic degradation of phenanthrene by sulfate-reducing bacteria which resulted in the formation of oxyphenol compounds, no such intermediate products were observed by Tausson and Vesselov (194) during the anaerobic degradation of naphthalene.

Von Oettingen (213) has reviewed the literature on the oxidation of benzene to polyphenols by experimental animals (see p. 476).

F. MODIFIED HYDROCARBONS AND PIGMENTS

From the observation that hydrogen was transferred from paraffinic hydrocarbons to methylene blue, as in a modified Wieland reaction, Tausz and Donath (196) conjectured that unsaturated hydrocarbons were formed by bacteria. The appearance of unsaturated hydrocarbons in kerosene cultures was attributed by Bushnell and Haas (19) to the dehydrogenating action of bacteria. Imelik (83) attributed an increase in the bromine index of petroleum being acted on by soil bacteria to the conversion of saturated hydrocarbons into unsaturated ones, but other workers (65,192) have presented evidence that unsaturated hydrocarbons are preferentially attacked (see p. 459).

In the gas phase of bacterial cultures growing on kerosene Thaysen (199) found 10.55% methane and 3.95% ethane. He credited microbial activity in water bottoms of kerosene storage tanks with being responsible for the production of explosive gas mixtures. ZoBell *et al.*

(235) have confirmed the liberation of volatile hydrocarbons, definitely methane and possibly traces of ethane, from paraffin oil being decomposed by marine bacteria. Rubber-digesting bacteria observed by Söhngen and Fol (160) split methane from caoutchouc.

Upon a basis of theoretical thermodynamic considerations and the interpretation of laboratory observations, Tausson and Aleshina (191) postulated that the general tendency is for anaerobic sulfate-reducing bacteria to convert paraffinic hydrocarbons into polymethylene or naphthenic hydrocarbons, for example:

$$4\ C_{10}H_{22} + CaSO_4 \longrightarrow 4\ CH_3C_6H_{10}CH(CH_3)_2 + 4\ H_2O + CaS + 184{,}400\ \text{cal.}$$

Unquestionably sulfate reducers do modify paraffinic hydrocarbons with the formation of a minimum of oxygenated carbon compounds, but virtually nothing is known regarding the chemical composition of the end products (235).

An unsaturated pigmented hydrocarbon, β-carotene was produced from paraffin oil by *Corynebacterium* species studied by Haas *et al.* (66,68). Two other carotenoid pigments and astacin were produced from paraffin oil by *Mycobacterium* species (67). Imelik (85) identified as hemipyocyanin the pigment produced by *Pseudomonas aeruginosa* during the decomposition of cyclohexane. Microorganisms growing on various kinds of hydrocarbons often produce pigments which impart a yellow, orange, red, brown, or other color to the medium. According to Slavnina (155b), certain hydrocarbon-oxidizing bacteria produced a brilliant green fluorescence by which they could be distinguished from closely allied species.

IX. Microbial Modification of Petroleum and Its Products

Petroleum may be modified wherever it occurs in contact with water under conditions favorable for microbial activity. The extent and character of the changes will be influenced primarily by the surface area of oil exposed to microbial enzymes, the kinds of organisms present, chemical composition of the oil, the environmental conditions, and time. The accumulation of oil in droplets or larger masses and its burial in sediments tend to protect it from contact with water or oxygen, thereby greatly retarding its destruction, but even in subterranean pools petroleum may be slowly attacked by anaerobic bacteria at the oil–water interface. Probably only in those environments where microbial activity is prevented by adverse pH, low E_h, toxic elements, antibiotics, lack of moisture or nutrients, enzyme inhibitors, or other unfavorable conditions is petroleum completely immune from microbial attack. Cyanide and urethane may be mentioned as examples of enzyme inhibitors which stopped the action of *Bacterium aliphaticum* on hydrocarbons (97), and there may be other types of enzyme inhibitors occurring naturally in sediments.

A. RATE OF OXIDATION OF OIL

Wagner (215) reported the destruction of crude oil by *Bacterium benzoli* at a rate exceeding 100 mg. per day in 100 cc. of mineral solution overlayered with oil. Layers of crude oil up to 2 mm. in thickness floating on mineral medium were perforated by bacteria within a week or two, after which the oil gradually disappeared, but layers thicker than 2 mm. were not noticeably affected by bacteria owing to a lack of free oxygen, according to Tausz and Peter (197).

Russian and American crude oils examined by Söhngen (158) were destroyed by soil aerobes at a rate as high as 0.75 g. of oil per day per square meter of oil surface exposed to the culture. In experiments of seven months' duration, Tausson and Shapiro (192) observed the bacterial destruction of crude and lubricating oils at rates ranging from 0.4 to 1.2 g. per day per square meter. From data given by Tausson (187), it is calculated that enrichment cultures of soil bacteria oxidized paraffin wax having a melting point of 78°C. at a rate of 1.93 g. per day per square meter. Naphthalene was oxidized as fast as 3.37 g. per day per square meter (185).

Mixed cultures of aerobic soil and marine microorganisms studied at the Scripps Institution (235) destroyed crude oils from nearly one hundred different fields at rates ranging from 0.03 to 0.5 g. per day per square meter. Approximately one gram of oil was accurately weighed into 100 cc. of inoculated mineral medium in glass bottles which gave an oil–water interfacial area of approximately 60 square centimeters. After 3 to 14 months' incubation at 28°C. the loss of oil attributable to microbial activity was determined by careful comparison with uninoculated controls.

The rate of oil oxidation could be greatly accelerated by dispersing the oil throughout the medium by emulsification or by absorption on particles of calcium carbonate, silica sand, diatomaceous earth, or other finely divided solids. Such dispersion of the oil also provided for more rapid multiplication of microorganisms. During the period of logarithmic increase it is estimated that aerobic bacteria destroyed oil at the rate of 4 to 318 × 10^{-13} mg. per cell per hour at 28°C.

B. EXTENT OF CHANGE

Thick layers of oil may be affected so slowly by microbial action that the only evidence of attack is to be found in the juxataposed water phase (increased bacterial population, reduced oxygen content, lowered *p*H, etc.). At the other extreme, oil in thin films on water or soil may be quantitatively oxidized to carbon dioxide and water.

The complete disappearance of crude oil from the water and beaches of San Francisco Bay following the wrecking of a tanker was shown by Beckman (10) to be due largely to bacterial action. In swamps where mosquito control presents a problem, Headlee and Miller (74) noted the destruction of films of oil attributable to microbial activity. Layers of oil 0.1 to 0.2 mm. thick placed on marshes and reservoirs to control mosquitoes were observed by Tausson (186) to be emulsified, perforated, and oxidized by bacteria in 7 to 10 days in the summer. When absorbed on small pieces of pumice to provide for better contact with bacteria or their enzymes, oil was decomposed much faster than were films of oil floating on the water.

The turbidity of mineral medium inoculated with soil bacteria and covered with a layer of heavy black Baku crude oil 1 to 5 mm. thick was observed by Tausson (187) to increase gradually due to the multiplication of bacteria and the emulsification of oil. Often the medium became discolored yellow or brown and a bacterial pellicle formed at the oil–water interface. After 4 days there was evidence of emulsification which increased until the layer of oil was perforated in places and, within 10 to 18 days, the layer of oil was broken into islands. After three weeks only a semisolid sticky resinous residue remained.

Examples of the disappearance of oil from surface soil as a direct result of microbial activity have been chronicled by Baldwin (7), Carr (21), Osnitskaya (128), and Tausson (186). The disappearance within a few days of crude oil, stove oil, or other petroleum products sprayed on soil or trees to kill weeds or insects must be due to hydrocarbon-oxidizing microorganisms.

Oil in subterranean deposits may have been modified by microorganisms throughout the geological ages. Although there is no conclusive evidence for such change, the occurrence of living bacteria at appreciable depths in petroliferous sediments (190,225) is highly suggestive. Ginsburg-Karagitscheva (57) has reported the presence of living bacteria in Tertiary formations, and the general absence of sulfates in certain formations indicates the activity of sulfate-reducing bacteria (56). Such bacteria were credited by Rogers (137) with depleting sulfates and contributing to the conversion of paraffinic hydrocarbons into naphthenic compounds. This function has been attributed to certain sulfate-reducing bacteria by Tausson and Aleshina (191). The possibilities of sulfate reducers modifying petroleum at the oil–water interface have been discussed by Baier (6), Schwartz and Müller (148), and ZoBell (230). Laboratory experiments have shown that bacteria alter the properties of crude oil in various ways (20,21,83,158,192,195,235).

Various ways in which bacteria may contribute to the release of crude oil from oil-bearing sediments have been outlined by ZoBell (228–230).

C. PETROLEUM PRODUCTS

The microbial modification of kerosene, gasoline, and other distillation products of petroleum has been reported by several investigators (19,20,58,97,158,189,192,196,214,221,223,234). An increase in the hydrogen sulfide content of natural gas was attributed by Kegel (102) to the activities of hydrocarbon-oxidizing bacteria in the sulfate-containing waters of trickling gas coolers. Hasemann (73) studied the decomposition of illuminating gas by bacteria.

Discoloration and the formation of gummy substances in gasoline and kerosene were shown by Haas (66) to result from the action of bacteria under certain conditions. Diesel fuels, lubricating oils, and paraffin oils were also attacked when stored in contact with water. Bacteria found by Thaysen (199) in the water bottoms of gasoline and kerosene storage tanks helped to account for the deterioration of these distillates, the formation of hydrogen sulfide, and the corrosion of metal tanks. Thin layers of kerosene on water containing soil bacteria became discolored and gradually disappeared, according to Tausson (186).

Recent studies by Allen (2) have shown that various microorganisms, in the water phase which is present below gasoline in storage, may have a pronounced deteriorating effect on the motor fuel. Bacterial activity may result in the formation of peroxides and gum in gasoline, leading to the precipitation of lead tetraethyl. Slime formation in paraffin oil was traced to bacterial activity by Scott (150). Samples of paraffin oil as well as castor oil, olive oil, and linseed oil were found by Milne (113) to be contaminated with microorganisms which presumably were growing in the oils.

Cutting and cooling oils used in machine shops are attacked by bacteria, which sometimes create foul odors, cause objectionable alteration of the oils, or contribute to dermatitis of workmen (36,37,107). Liberthson (108) incriminated bacteria in cutting oils as being responsible for the breaking of emulsions, the failure of preservative and inhibiting compounds, and the corrosion of metallic surfaces.

Fleming (49), Gainey (53), and Greig-Smith (62) showed that, due to its susceptibility to microbial attack, paraffin wax cannot be depended upon to protect objects buried in the soil. Lavers and Illman (106) observed that paraffin wax employed to coat packaging materials supported an abundant growth of molds. The deterioration of paraffin wax by microorganisms has been reported by Jensen (92,94), Tausson (183), Tausz (195), Umbreit (205), and by many others (226).

Asphalt, employed for paving streets, air strips, etc., or for waterproofing basements, may be attacked by bacteria in moist soil (169, 226). In the presence of moisture the asphalt coating on concrete blocks was destroyed by soil fungi, according to Hundeshagen (81).

X. Microbial Decomposition of Rubber Hydrocarbons

Pure India rubber, also called caoutchouc, consists of polymerized olefinic hydrocarbons represented by the empirical formula $(C_5H_8)_n$. Caoutchouc is produced by a wide variety of plants, the best yields being obtained from the families Apocyanceae, Euphorbiaceae, and Moraceae. The commercial product is obtained mostly from the plantation rubber tree, *Hevea brasiliensis*. Lesser quantities of latex are obtained from *Hevea benthamiana*, *Castilla ulei*, *C. elastica*, *Manihot glaziovii*, *Fiscus elastica*, *Funtumia elastica*, and other wild rubber trees. High percentages of caoutchouc also occur in the Haitian shrub, *Cryptostegia gandiflora*, the guayule plant, *Parthenium argentatum*, certain milkweeds of the genus *Asclepias*, dandelions of the genus *Taraxicum*, and scores of other plants.

Synthetic rubbers or elastomers, including buna types, thiokols, neoprene, chemigum, butyl rubbers, and hundreds of others, are essentially polymers or copolymers of butadiene, isoprene, isobutylene, styrene, acrylonitrile, and related unsaturated hydrocarbons. Manufactured rubber articles are prepared by compounding natural or synthetic rubber with vulcanizing agents, accelerators, softeners, fillers, pigments, and other organic or inorganic agents to give certain desirable properties of elasticity, resiliency, wearing qualities, heat resistance, vulcanizability, tensile strength, conductivity, inertness toward solvents, color, etc. Antimicrobial agents are sometimes added because natural, synthetic, and compounded rubbers are susceptible to microbial decomposition under certain conditions (232,233).

The microbial utilization of caoutchouc was first reported by Söhngen (159) in 1913. Söhngen and Fol (160) isolated from soil and ditch water several cultures, including *Actinomyces alba*, *A. chromogenes*, *A. elastica*, *A. fuscus*, *Bacillus mesentericus*, *Mycobacterium lacticola*, *M. rubrum*, and *Pseudomonas fluorescens*, which could obtain their carbon and energy requirements from pure rubber in mineral medium.

The red spots which often appear on unpreserved sheets of raw or crepe rubber stored in moist places were shown by Arens (4) to be due to the growth of *Serratia marcescens* with other organisms. From damaged crepe rubber Bloomendaal (16), DeWilderman (33), and Eaton (38) isolated several varieties of chromogenic bacteria, which were held to be responsible for the "spot disease" or perforation of rubber.

The loss of weight and decreased elasticity of moist sheets of plantation rubber during prolonged storage were attributed by DeVries (31,32) to the activities of *Aspergillus* and *Penicillium* species. Among the many species isolated by Corbet (28) from fermenting hevea latex were *Alcaligenes denieri*, *Bacillus pandora*, *Gaffkya verneti*, *Micrococcus chersonesia*, *M. eatoni*, *M. epimetheus*, *M. ridleyi*, and *Torulae heveae*. Novogrudski (127) found in soil and on the leaves of rubber plants species of bacteria, actinomyces, and molds which decomposed rubber and decreased its viscosity.

Kalinenko (100) noted during one month's incubation at 28°C. the destruction of from 20 to 40% of the rubber in latex by *Actinomyces aurantiacus*, *A. longisporus ruber*, *Aspergillus oryzae*, *Penicillium* species, and several cultures of mixed microflora commonly found in soil.

Decreases in the yield of rubber from guayule latex of as much as 15 to 20% in six weeks at 37°C. and deterioration in the quality of the remaining rubber were shown by Spence and associates (162,163) to be caused by soil microorganisms. Four species of *Actinomyces* and several species of anaerobic bacteria, which attacked rubber hydrocarbons, were isolated from guayule latex (161). Allen *et al.* (3) have investigated the decomposition of guayule resins by microorganisms.

ZoBell and Beckwith (232) observed the oxidation of pure caoutchouc as well as several types of compounded rubber, both natural and synthetic, by *Bacterium aliphaticum*, *Pseudomonas fluorescens*, *P. neritica*, *Serratia marcescens*, *Vibrio marinofulvus*, certain strains of *Escherichia coli*, and several cultures of mixed microflora from the sea or soil. Recognizing that rubber products exposed to water for prolonged periods are subject to microbial attack, Dimond and Horsfall (35) recommended that such products be compounded with antimicrobial agents to prevent the microbial oxidation of rubber.

XI. Assimilation of Hydrocarbons by Animals

Although there have been many reports (134,176) that petroleum hydrocarbons pass unabsorbed and unchanged through the intestine of man and other mammals, it is now known that hydrocarbons may be assimilated under certain conditions. It is still indeterminate, however, the extent to which intestinal bacteria contribute to the digestion of hydrocarbons but there is pretty good evidence that some animals have hydrocarbonoclastic enzymes. The author believes that careful investigations will reveal that such enzymes occur in most classes of animals.

A. PARAFFINIC HYDROCARBONS

When Channon (22) included squalene, an unsaturated hydrocarbon, $C_{30}H_{50}$, in the diet of rats there was evidence of some absorption. The cholesterol content of the livers of such rats increased about 100% and there was also a marked increase in the content of unsaponifiable matter. The absorption of mineral oils by rats and pigs was proved by Channon and Collinson (23), who demonstrated an increase in the hydrocarbon content and a decrease in the iodine number of the livers of animals fed on a diet containing liquid paraffin. The recovery from the excreta and tissues of cats of much less *n*-hexadecane than the amount fed led Channon and Devine (24) to conclude that part of the hydrocarbon was converted into other unidentified products in the body. Similar conclusions were reached by El Mahdi and Channon (44) after noting that the absorption of from 50 to 100 mg. of *n*-hexadecane per day from the alimentary tract of the rat was accompanied by an increase in tissue lipides.

Stryker (176) microscopically and chemically examined the mesenteric lymph nodes, liver, spleen, and other tissues of post-mortem human subjects, guinea pigs, rats, and rabbits to establish the absorption of small amounts of mineral oil from the intestinal tract. The absorption of paraffin oil by rats was demonstrated by Frazer *et al.* (51) by histological, biochemical, and chylomicrographic methods.

Employing material tagged with heavy hydrogen, Stetten (168) established that rats absorbed 7,8,9,10-tetradeuterio-*n*-hexadecane and oxidized it partly to fatty acids. The catabolic rate of the hydrocarbon was followed by the content of deuterium in fatty acids and body water. Hexadecane was believed by Stetten to be absorbed from the intestine without the intervention of bacteria and converted first into palmitic acid by oxidative attack on the terminal methyl group, apparently in the liver.

Larvae of the petroleum fly, *Psilopa petrolii*, occur in large numbers living in pools of crude oil waste near wells at Sante Fe Springs, California. Doubting that they could digest oil, Thorpe (202) suggested that the fly larvae obtained their food from the ingestion of bits of organic matter, bacteria, or protozoa. *Amoeba proteus* was reported by Dawson and Belkin (30) to be unable to digest mineral oil, although various vegetable and animal oils were assimilated. Evidence that there are many bacteria which can grow at the expense of hydrocarbons in crude oil has been summarized in preceding sections of this paper (p. 470).

B. AROMATIC HYDROCARBONS

As a detoxication mechanism, animals are able to oxidize a large variety of aromatic hydrocarbons when administered in sublethal doses (70,211). Rabbits were shown by Neubauer (121) to be able to oxidize ethylbenzene to benzoic acid and an alcohol, $C_6H_5CHOHCH_3$. Most of the toluene orally administered to dogs was detected in their urine as hippuric acid by Knoop and Gehrke (104).

Jaffé (90) isolated muconic acid from the urine of dogs following their feeding with benzene. Rabbits were also found to be able to oxidize benzene to muconic acid and phenol. The observation was repeated with dogs and rabbits by Neumaerker (122) and Thierfelder and Klenk (201). Benzene was found by Gadaskin (52) to be oxidized primarily to phenol, which could be detected in the blood within 40 minutes after administration and a little later in the urine.

Bernhard and Gressly (11) isolated muconic acid containing deuterium from the urine of rabbits to which isotopic benzene, C_6D_6, had been administered. Handler and Perlzweig (70) reported the oxidation of *p*-cymene to cumic acid by sheep, the oxidation of 3,4-benzopyrene to 8-hydroxy-3,4-benzopyrene and 3,4-benzopyrene-5,8-quinone by mice, and the oxidation of 1,2,5,6-dibenzanthracene to a dihydroxy compound by rats, mice, and rabbits. Several other examples of the oxidation of aromatic hydrocarbons by higher animals are given by Von Oettingen (211). He (213) has reported the oxidation of benzene to polyphenols, toluene to benzoic acid, *p*- and *m*-xylene to the corresponding toluic acids, and propylbenzene to benzoic acid.

An increase in the excretion of glucuronates and ethereal sulfates by dogs following the administration of benzene, anthracene, or phenanthrene indicated to Stekol (166) that these hydrocarbons were metabolized.

XII. Production of Hydrocarbons by Microorganisms

Careful examination of their tissues reveals that most plants synthesize hydrocarbons (25,26,142)—very appreciable amounts by some plants such as the Jeffrey pine, guayule plant, and rubber tree. Bacteria and allied microorganisms also produce hydrocarbons either as a part of their protoplasm or as end products of catabolism. In the latter category methane is the only hydrocarbon that has been demonstrated to be produced in large quantities.

Since 1875, when Popoff (132) first demonstrated the formation of methane from the fermentation of cellulose, it has been shown that a large variety of organic compounds as well as molecular hydrogen may provide the energy necessary for the formation of methane (7,231). It is now known from the work of Barker (8) and Stephenson and Stickland (167) that methane is formed primarily from the reduction of carbon dioxide or other one-carbon-atom compounds:

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O$$

Conclusive proof is lacking for the microbial formation of any gaseous hydrocarbon other than methane as a catabolic product, although there are some highly suggestive reports. For example, Neave and

Buswell (120) reported finding from 0.7 to 12.1% of ethane in the gases produced by bacteria during the fermentation of sewage sludge and distillery slop. Rudolfs and Heisig (140) found, beside methane, hydrogen, and carbon monoxide in the gas given off from fermenting sewage, also from 0.6 to 2.8% of "illuminating gas." Traces of ethane, propane, pentane, and butadiene were detected by Rawn *et al.* (135) along with large quantities of methane in the gas from sewage sludge digestion. The formation of gaseous hydrocarbons beside methane from the fermentation of tributyrin in the presence of base exchange substances was reported by Taylor (198).

Accounts in the literature on the formation of benzene and toluene from the bacterial decomposition of phenylalanine, tyrosine, or other amino acids containing the benzene nucleus have not been confirmed by recent work. Intestinal microflora attacking tyrosine were found by Sieke (153) to form phenol. Phenol and/or *p*-cresol but no benzene or toluene was produced by either mixed or pure cultures of soil and marine organisms investigated by Research Project 43 of the American Petroleum Institute (235).

The conversion of cinnamic acid into styrene by *Aspergillus niger* has been reported by Herzog and Ripke (75). Fergus (48a) has summarized the evidence for the synthesis of ethylene by *Penicillium digitatum* and other microorganisms.

Carotenoids and other pigmented hydrocarbons are known to be produced by a good many species of both aerobic and anaerobic bacteria. The production of liquid and solid paraffinic hydrocarbons ranging from $C_{10}H_{22}$ to $C_{25}H_{52}$ by sulfate-reducing bacteria was reported by Jankowski and ZoBell (91). Further work has established that naphthenic hydrocarbons are also produced by sulfate reducers (235). The hydrocarbons are produced as a part of the bacterial cell substance, the total quantity being of the order of only 0.5% or less of the carbon content.

XIII. Summary and Conclusions

Virtually all kinds of hydrocarbons are susceptible to attack by bacteria and allied microorganisms. This generalization is based upon observations on nearly one hundred pure hydrocarbons ranging in complexity from methane to dibenzanthracene and on several hundred mixtures of hydrocarbons. The latter include natural gases, ligroins, gasolines, kerosenes, benzines, lubricating oils, fuel oils, paraffin waxes, tars, crude oils, asphalts, asphaltenes, synthetic and natural rubbers, etc. Benzene, toluene, xylene, naphthalene, and other hydrocarbons sometimes used as preservatives are decomposed by certain microorganisms.

A good many species of bacteria, yeasts, and molds have been shown to produce hydrocarbonoclastic enzymes. Employed as criteria of hydrocarbon attack have been microbial multiplication, oxygen consumption, carbon dioxide production, modification of hydrocarbons, and methylene blue reduction in mineral media containing hydrocarbons as the sole source of carbon and energy. Similarly, sulfate and nitrate reduction have been employed as criteria for the attack of hydrocarbons by certain anaerobic bacteria.

Rapid assimilation requires the employment of special techniques to disperse in aqueous media hydrocarbons having low solubilities. Emulsifying the hydrocarbons in aqueous media or dispersing them adsorbed on the surface of sand, asbestos fibers, diatomaceous earth, or other particulate materials has produced good results.

Hydrocarbonoclastic microorganisms appear to be quite widely and abundantly distributed in soil, natural bodies of water, and in submerged sediments. They are especially abundant in oil-soaked soil around oil fields and refineries. Certain microorganisms develop the ability to attack hydrocarbons after being grown for several generations in nutrient medium enriched with hydrocarbons, which indicates adaptive enzyme formation.

The ability of microorganisms to attack hydrocarbons is highly specific. In general, paraffinic hydrocarbons are attacked more readily and by more species than cyclic compounds. The susceptibility to oxidation appears to increase with chain length up to about fifteen or twenty carbon atoms, above which extremely low solubility makes hydrocarbons less vulnerable to attack. Double bonds in open-chain hydrocarbons and branching or side chains in all kinds of hydrocarbons increase oxidizability.

Carbon dioxide and microbial cell substance are the principal products resulting from the oxidation of hydrocarbons. Organic acids, aldehydes, ketones, alcohols, oxyphenols, pigmented substances, and modified hydrocarbons are also produced.

Hydrocarbons can be expected to be attacked wherever crude oil or its distillation products are in contact with water under conditions favorable for microbial multiplication. When thoroughly dispersed under aerobic conditions, as in soil soaked with oil, the hydrocarbons may be rapidly and quantitatively oxidized. The gradual disappearance of oil spilled on waterways or on soil around petroleum works is believed to be due largely to microbial activity. Hydrocarbon-oxidizing microorganisms may modify crude oil or prevent its accumulation in certain environments. The activity, presence, or products of bacteria which oxidize volatile hydrocarbons in soil overburdening subterranean deposits may serve as indicators in so-called geomicrobiological prospecting methods. The use of microorganisms in the recovery, refinery, and conversion of hydrocarbons has almost unlimited possibilities in the petroleum industry.

Films of oil spread on bodies of stagnant water or on the leaves of vegetation to control mosquitoes or other insects may be destroyed by microbial activity. The growth of bacteria in cooling and cutting oils in machine shops has been responsible for objectionable conditions. Without proper preservatives, hydrocarbon products buried in soil or water can be expected to have a short life as waterproofing or insulating agents. Pharmaceutical preparations containing hydrocarbons emulsified in water as well as paraffin wax used to coat packaging materials support the growth of microorganisms.

Bacteria in the gut of animals may contribute to the digestion of hydrocarbons, although there is evidence that rats, cats, dogs, and other experimental animals absorb and assimilate both paraffinic and aromatic hydrocarbons in small amounts, independent of the action of microorganisms.

Beside methane, the microbial production of which is well authenticated, smaller amounts of ethane, propane, pentane, butadiene, styrene, carotene, and other hydrocarbons have been reported to be produced by microorganisms. Liquid and solid paraffinic hydrocarbons as well as naphthenic hydrocarbons have been demonstrated in the cell substance of bacteria utilizing fatty acids.

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Contribution No. 439

Early Life History and Larval Development of Some Puget Sound Echinoderms

by

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EARLY LIFE HISTORY AND LARVAL DEVELOPMENT OF SOME PUGET SOUND ECHINODERMS

With Special Reference to *Cucumaria* spp. and *Dendraster excentricus*[1]

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It is a pleasure to acknowledge the unfailing interest and guidance of Professor Kincaid in the study of the biology of the Puget Sound region. His appreciation of the importance of life history and general plankton studies to an understanding of the biology of the sea has led to this report. Thanks are also due to the late Dr. J. E. Guberlet for supervising some of the embryological work here reported, and to Dr. T. C. Frye, former director of the Puget Sound Biological Station, as well as to Dr. T. G. Thompson, Director of the University of Washington Oceanographic Laboratories, for facilities at Friday Harbor.

Introduction

Only a few investigations have been published dealing with the life histories and developmental stages of Puget Sound echinoderms. The earliest and most comprehensive report applicable to the holothurians and echinoids of this area is that of Mortensen (1921) who, while at Nanaimo, B.C., in 1915, studied more or less completely the early life histories of *Strongylocentrotus franciscanus* Agassiz, *Dendraster excentricus* (Eschscholtz), and *Stichopus californicus* (Stimpson). Several species of local asteroids were also studied. No larvae were carried through metamorphosis, and only fragmentary information was obtained for some of the species. Courtney (1927) studied the sexual maturity of *Stichopus californicus* at Friday Harbor, and Johnson (1930), working in the same area, reared and studied all larval stages of *Strongylocentrotus franciscanus* to metamorphosis and reported (1932) on the occurrence of echinoderm larvae in the plankton over a period of four years.

The present report deals only with the Echinoidea and Holothuroidea and covers several years of data gathered at Friday Harbor prior to 1934. Publication has been delayed in the hope that more details might be included on the life histories of some of the forms here dealt with in only a preliminary way. Additional observations were made during the period June 23 to August 23, 1947, but the holothurians had already ceased spawning with the exception of *Stichopus*. *Dendraster* spawned freely permitting a check of the earlier work.

Holothuroidea

It is known that of all the echinoderms, with the exception of the crinoids, the holothurians, especially the Dendrochirotes, the order to which the species here discussed belong, are the most difficult subjects for artificial fertilization (Mortensen, 1921). Hence, unless natural spawning can be induced in aquaria, it is necessary to piece together the life history by rearing and identifying embryos and larvae that have been collected from the plankton. This is a less certain method than direct rearing from the known egg, and it is also a laborious one, since the larvae develop so slowly that several months of observation are necessary to accomplish results.

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[1] Contributions from Scripps Institution of Oceanography of the University of California, New Series No. 439.

The occurrence of the embryos in the plankton is, of course, a direct index of the breeding season of the species involved, and it is therefore here given in some detail. The larvae are planktonic only a little over a week.

During the spring months, mainly March, April, and May, for the four years 1927 to 1930, certain holothurian larval forms occurred in large numbers in the plankton taken in the channel between the Puget Sound Biological Station (now University of Washington Oceanographic Laboratories) and Brown Island. In earlier plankton hauls they were common in the samples taken in the bay in April 1924, but records were not complete for that year, and no records were kept for the spring months of 1925 and 1926.

A tendency of the larvae to accumulate in streaks or patches made quantitative plankton sampling difficult, but the general collecting data for 1929 and 1930, together with a summary (Table I) from a separate investigation (Johnson, 1932), will serve to indicate the spawning season, the relative abundance, and the fluctuations that were observed.

TABLE I

SUMMARY OF THE AVERAGE MONTHLY OCCURRENCE OF HOLOTHURIAN LARVAE IN THE PLANKTON AT FRIDAY HARBOR, WASHINGTON, 1924-1929

(Only the months in which the larvae occurred are included)

F=frequent; C=common; A=abundant; VA=very abundant

Year	*March*	*April*	*May*	*June*
1924..........	....	C	....	....
1927..........	VA	none	none	none
1928..........	VA	F	C	none
1929..........	VA	C	A	F

In the early developmental stages, the larvae are very buoyant and float at or near the surface of the water. They were usually collected with a 10-inch No. 15 plankton net towed at the surface, but on May 4, 1929, they had gathered in such numbers along a line of drift between two tidal currents that eighty of them were dipped up in one scoop with a pint jar. Later the same day, three hundred larvae were secured in a two-hundred-meter plankton tow. Between March 31 and May 3, 1929, only an occasional specimen was found in the plankton, and they were apparently absent between May 15 and June 10. In 1930 the following results were obtained. A two-hundred-meter tow taken on March 25 and another on March 28 yielded two and seven larvae respectively. On April 1, a four-hundred meter tow yielded 150, and on the following day an eight-hundred-meter tow caught 140 specimens.

Systematic collecting was not carried on elsewhere in the San Juan Archipelago, but casual observations in 1930 showed spawning to be general in the area, for the larvae were common in San Juan Channel, in Griffin Bay, and at the Olga–Orcas Island ferry landing at the same time as they appeared in the plankton in Friday Harbor. The appearances were generally sporadic, suggesting spontaneous waves of spawning over a large population. Such outbursts of spawning are characteristic of a number of other marine invertebrates, for example, oysters, mussels, and annelids.

Supplementary information on the breeding season was obtained by examining the sexual condition of adult specimens collected from different localities in the neighborhood. In 1929, thirty *Cucumaria chronhjelmi* Théel,[2] collected at Friday Harbor on May 12, showed all females to be spent, but the male gonads were filled with active sperms. A few days later another collection revealed one female with ovaries filled with opaque green eggs resembling some of the embryos found in the plankton, but the males were all spent. At this time several *Cucumaria miniata* (Brandt) were examined and found to be spent or sexually immature. One of three *Psolus chitonoides* (Clark) was found to have ovaries filled with bright red-orange eggs resembling certain embryos taken from the plankton in March and again on June 10.

On July 8, 1930, twenty *Cucumaria piperata* (Stimpson) were dredged in East Sound, Orcas Island, and upon examination showed twelve females spent and two females with a few opaque green eggs. Of the six males, five were spent, and the sixth had a few active sperms. Fertilization of the eggs with these sperms was attempted but without success.

On May 4 and 12, eggs and sperms were taken from *Stichopus californicus* (Clark), and after artificial fertilization development continued to the gastrula stage, indicating that some individuals of this species are ripe in May. This is in general agreement with Mortensen (1921), who found this species to be ripe at Nanaimo, B.C., in June. On the other hand, it differs from Courtney's conclusion (1927) that *S. californicus* does not spawn until late summer.

Culture of the Larvae

The holothurian larvae secured from the plankton as mentioned in the preceding section were brought to the laboratory and placed in sea water in covered, clear glass jars of about 1,500 ml. capacity. The cultures were kept at an even low temperature by surrounding the jars with running water previously cooled by being passed through pipes submerged in the sea at the laboratory. At first the water on the cultures was changed daily by removing the animals to another dish with a pipette, but after a few days they became attached and the water could be poured off and a fresh supply added at once to the same dish. This change was usually made weekly.

Cultures of varying numbers of individuals were set up on the following dates:

In 1929 one culture was set up on March 24, one on March 31, two on May 4, and one on June 10—corresponding to the dates when the larvae were most abundant in the plankton. Four cultures containing approximately seventy-five specimens each were started April 1 and 2, 1930.

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[2] According to Ricketts and Calvin (1939) this species is the same as *Cucumaria quinquesemita* Selenka.

The eggs are well supplied with yolk, and this is apparently sufficient to carry the early larvae through the pelagic stage until they settle on the bottom and begin feeding. Diatoms, mainly *Nitzschia* and *Navicula,* were added as food and permitted to grow in the culture dishes to a point where they formed a thin brown covering on the walls of the dishes. After settling on the bottom and sides of the dishes, the little cucumbers could be seen browsing on the diatoms, and their stomachs were filled with brown masses.

The larvae collected in March 1929 were either green or orange in color. These colorations were at first considered to be individual variations of no importance, but the green larvae developed so much more rapidly than did the others that it became apparent they must be of a different species. Consequently the orange-colored larvae, which were less numerous, were removed to a separate culture dish, and considered only supplementary to the study of the green larvae, which proved to be mainly *Cucumaria chronhjelmi.*

DEVELOPMENT OF CUCUMARIA CHRONHJELMI

All of the specimens collected from the plankton were very opaque, 0.35 mm. to 0.55 mm. long, and somewhat egg-shaped. They floated with the large end up, and rotated actively in a clockwise manner. Preserved and sectioned material proved them to be in various stages of development, ranging from morulae through ciliated blastulae and gastrulae to a few young larvae with an atrium and tentacles (Figs. 1, 2, 3). There is no auricularian stage, such as is typified locally by the larvae of *Stichopus californicus* and such as is characteristic also of the Holothuriidae and of the Synaptiidae. The gastrula develops directly into the barrel-shaped "Doliolaria" larva, comparable to that found in some other Cucumariidae (*Cucumaria* and *Psolus*) and reported also in *Caudina chilensis* (Ibana, 1930). At no time was it definitely determined from living specimens whether or not the cilia formed into ciliated bands, but stained and cleared specimens showed three narrow dark bands completely or partially encircling the body. Oshima (1921) found that the cilia were not arranged into bands in the early developmental stages of *C. echinata,* and Newth (1916) found uniform ciliation with no ciliated bands at any stage in *C. normani.*

The swimming period continued for about a week, during which time an atrium developed on the ventral side just anterior to the mid-body, and within this cavity could be seen five primary tentacles (Fig. 3). As the atrium and tentacles grew larger, the latter were repeatedly extended and withdrawn through the opening of the atrium (Fig. 4). Gradually the atrium and tentacles moved forward until they occupied the anterior end of the body, pushing upward the anterior dorsal surface and thus forming the preoral hood, which was later absorbed (Fig. 6).

Before the atrium had completed its movement forward, the two primary pedicils appeared as cylindrical structures on the posterior ventral surface of the body (Fig. 3). Before the preoral hood was completely absorbed, the primary pedicils were being used to attach the larva to the bottom of the dish. The development of two primary pedicils is in agreement with findings for other species of *Cucumaria,* for example *C. planci* by Selenka (1876) and *C. echinata* by Oshima (1921). Edwards (1909) found only one primary pedicil in *Holothuria floridana.* The number of primary tentacles found in our larva is also in agreement with the number found in *C. planci* and *C. echinata*, but differs from *H. floridana*, which had four primary tentacles, according to the above authors. The development of the primary pedicils occurred at the end of one week and marked the beginning of attachment to a substratum. The length of time recorded in this paper is from the beginning of the culture, but since the embryos were in or near the gastrula stage when placed in the culture, about two days should be added, if one may judge by the rate of development Selenka and Oshima observed for their species of *Cucumaria*.

While feeding, the larvae are attached by the pedicils and reach about with the tentacles exploring the area for food, which, when found, is carried into the mouth by the use of one tentacle at a time.

The canal within each tentacle and pedicil is filled with fluid in which there are many amoebocytes that flow rapidly back and forth. The canals of the two primary pedicils arise as branches from the posterior end of the ventral radial canal as observed in specimens flattened under a cover glass (Fig. 5). No other radial canals were as yet fully developed. Selenka observed that in *C. planci* the ventral radial canal also developed first.

Following the development of the five primary tentacles during the first week, there was no increase in the number of tentacles until the end of 42 days. Ludwig (1891) found that *C. planci* showed no increase in the number of tentacles until the end of 116 days. In our larvae the sixth and seventh tentacles appeared simultaneously at the end of 42 days. These occurred one on either side, immediately adjacent to the ventral pair of primary tentacles (Fig. 9, St_1). The eighth and ninth tentacles arose one on each side between the sixth and seventh and the ventral pair in about 75 days, while the tenth and last tentacle occurred at the right of the dorsal tentacle (Fig. 10, St_2 and St_3). This order varies from that given by Oshima (1921) for *C. echinata*, in which the unpaired tentacle developed to the right of the mid-dorsal tentacle before the ninth and tenth appeared one on either side of the ventral pair. In 1929 the number of tentacles was complete within three months.

The order of development of the tentacles was easily followed because the ventral pair did not branch before about the sixth week, at which time they divided only once dichotomously at the tip (Fig. 8). They did not branch again until a considerable time after the tenth tentacle was developed. The study was further aided by the fact that the ventral pair of tentacles remained smaller than the others. Oshima (1921) found that the ventral pair in *C. echinata* branched twice dichotomously and then remained so for some time. In the present species, none of the tentacles were branched when first extended from the atrium, but the three dorsal ones divided into two equal branches at the end of the first week. The lateral branches appeared at frequent intervals and were arranged spirally around the tentacles (Figs. 8 and 11). Each branch and sub-branch was connected by a canal continuous with that of the main tentacle, and the end of each branch was covered with hyaline papillae.

Only the two primary pedicils appeared before the twenty-fourth day, at which time the third pedicil was developed anterior and to the left of the mid-ventral line. Shortly afterward, the fourth became apparent anterior to the third and to the right of the mid-ventral line. The fifth appeared still further forward and on the left of the mid-ventral line (Fig. 7). Their position would indicate that they branched from the ventral radial canal. Ludwig (1891) found that the first five pedicils in *C. planci* appeared in the same order and position, but it was 45 days before the third pedicil appeared. When the larva had eleven pedicils there were only two which were not ventral. Both of these were on the anterior dorsal surface, one somewhat to the left, and the other to the right. This agrees with *C. echinata,* in which most of the early pedicils are ventral. At no time were the pedicils provided with hyaline papillae as were the tentacles.

At the end of the first week, a complete perforated calcareous plate could be seen on the posterior dorsal surface of the body, and there was also one spirally curved but incomplete plate around each pedicil. The plates which soon formed on the tentacles were like those of the pedicils. The entire body was covered with systematically arranged plates by the end of two weeks, and each pedicil had three plates (Fig. 6). Later increases in the size of the larva left spaces between the plates, and small new plates developed between the earlier ones (Figs. 8 and 11). The plates on the tentacles increased in number until the latter were completely covered when not extended, while the plates on the pedicils became so numerous that they overlapped when the pedicils were contracted. The calcareous ring was visible through the body wall at six months but was not completely formed when observations were made at ten months. As the larva grew older it lost the green color and became somewhat transparent.

Older specimens cleared in clove oil after the plates had been removed by weak acid were quite satisfactory for gross internal study. At three months, the alimentary canal with its characteristic forward bend is similar to that of the adult. At this time the branchial trees could not be seen, but at seven months a living specimen showed two unbranched tubes leading from the cloaca laterally and extending forward to the bend of the stomach. Successive waves of contraction started in the cloaca and ran the length of the tubes. The cloaca itself constantly opened and closed, taking in and ejecting a stream of water.

The specific identification of the larvae described above is based on the following features:

(a) arborescent branching tentacles characteristic of the order Dendrochirota, thus eliminating the local genera *Stichopus, Molpadia, Leptosynapta,* and *Chirodota.*

(b) two primary pedicils characteristic of the genus *Cucumaria.* (According to Bush [1921] there are five species of *Cucumaria* in the Friday Harbor area.)

(c) terminal position of the atrium and tentacles, thus eliminating the local species of *Psolus,* which has these structures located on the anterior dorsal surface at an early stage (2 mm.) as shown by two specimens reared in cultures and by similar-sized specimens collected in the field.

(d) the calcareous ring, which, though not completely formed at 10 months, resembles most closely the ring found in young *Cucumaria chronhjelmi* collected in the field (Figs. 12 and 13). It appears that the two small anterior points on the radial plates of the post larva are later united by deposition of calcareous material. The posterior prolongations of these plates as they occur in older stages were not completely developed.

(e) the two ventral tentacles remain small as in adults of that species.

(f) the embryos and early larvae are green and opaque similar to the eggs of *C. chronhjelmi*.

(g) the body and the tentacular plates are like those of the adult of that species (Figs. 14 and 17).

(h) *C. chronhjelmi* is an abundant species in the area and could be expected to produce many larvae.

Observations on Other Holothurian Larvae

The observations on these are only preliminary and useful mainly as a guide to further study, which should include also the relatively scarce *C. lubrica*. The orange-colored embryos collected from the plankton were cultured only in 1929, but they also occurred in considerable numbers in the plankton in 1930. Several points indicate that they were produced by *Cucumaria miniata*, which is abundant in the area. The gonads of that species are reddish-brown, suggesting the production of orange-colored eggs. The embryos set up in 1929 were cultured for 90 days, yet the tentacles remained directly anterior, proving that they could not be *Psolus chitonoides*, a less abundant species which also has orange-red eggs and embryos. In that species the larvae 2 mm. in length have already assumed the form of the adult with the flat ventral surface and the anterior dorsal atrium.

In 1930 a few larvae that had settled on the bottom were secured from field collections along the shore. These all came from algal holdfasts from depths of two to fourteen meters and gave the following results: four specimens of *C. chronhjelmi* 1.5 mm. to 2.2 mm. (in cultures this species grew to 4.5 mm. in 4 months); four specimens of *C. populifera* 1.0 mm. to 2.0 mm.; two specimens of a Dendrochirota 0.5 mm. to 1.0 mm.

Four cultures of green embryos set up on April 1 and 2, 1930, from plankton collections at Friday Harbor showed the following proportions of larval species in July, when they had developed to a stage showing at least some adult specific characteristics: 187, *C. chronhjelmi*; 5, *C. populifera* (?); 3, *C. piperata* (?).

The specimens mentioned as *populifera* were tentatively classified as such because of the spires or towers on the calcareous plates on the body and pedicils (Fig. 16). The larvae called *piperata* had relatively solid plates (*i.e.*, few perforations) on the tentacles and pedicils, in agreement with the condition found in adults of that species (Fig. 15).

Dendraster excentricus

This sand dollar occurs abundantly on the sandy bottom of False Bay near Friday Harbor, Washington, and is common at many other localities along the west coast from Alaska to Lower California. Only fragmentary information is available on its life history, though Mortensen (1921) succeeded in rearing the pluteus larva and has presented some field data on the rate of growth of metamorphosed specimens collected from the sea and believed to be 1, 2, and 3 years old. He, however, did not study the early embryological stages. He also left some minor features pertaining to the larval skeleton in doubt, and his larvae failed to undergo metamorphosis.

METHODS OF CULTURE AND BREEDING SEASON

The first cultures were set up on June 23, 1931, with eggs and sperms from specimens collected at False Bay. A few males spawned spontaneously in the laboratory, but it was necessary to obtain eggs by breaking away a portion of the test and removing the ripe ovary. Shortly after insemination, the eggs were washed several times with fresh sea water and the cultures thinned so that only a single uncrowded layer of eggs was on the bottom of each culture dish. The water used in washing and in subsequent changings was always filtered through No. 20 silk bolting cloth. Mixed diatoms, mainly *Nitzschia* and *Navicula*, were added as a source of food for the older larvae. A low temperature was maintained by placing the culture dishes in a tray of running water maintained near the normal seasonal temperature of the bay.

From these cultures normal larvae developed, but metamorphosis, though well begun, was not completed despite the fact that many of the specimens lived and appeared normal for more than 41 days.

The study was not resumed again until September 2, 1933, when adult animals were again collected at False Bay. This time, after a few hours on a moist cement tray, several specimens, both males and females, spawned spontaneously. From these the sex products were collected and cultures set up as before. The highest temperature recorded for the cultures was 16.1° C., on September 5, and the lowest, 8.0° C., on November 13. This is a greater range than experienced by the 1931 cultures.

The occurrence of ripe specimens in September is of more than passing interest, for it has been generally believed that the main spawning in this area takes place early in spring before the end of June. At Nanaimo, B.C., Mortensen (1921) found specimens to be ripe in May and June, but he did not investigate any other season. Plankton hauls taken in the bay at Friday Harbor yielded a few four-armed *Dendraster* larvae on October 12, indicating that spawning was perhaps rather general in the area during that month.

LARVAL DEVELOPMENT AND METAMORPHOSIS

The eggs are transparent, 0.1 mm. in diameter, and are surrounded by a thick highly transparent gelatinous mass with numerous purple pigment granules. The developing embryo does not escape from this mass until the late blastula or early gastrula stage.

In temperatures ranging from about 13° to 14° C., the rate of development is approximately as follows: 2-cell stage, 20 min.; 4-cell stage, 60 min.; 8-cell stage, 1 hr. 30 min.; 16-cell stage, 1 hr. 45 min.; early blastula, 3 to 4 hrs.; gastrula with calcareous star, 24 hrs.; four-armed pluteus larva, 46 hrs. There is a good deal of variation in the rate of development, especially after the cleavage stages and formation of the gastrula. Owing to retardation, the four-armed larvae often occur in the same culture together with advanced eight-armed stages.

The early embryological development is similar to that of other echinoids. The blastula and gastrula (Figs. 21 and 22) are beautifully clear, and are covered with short cilia; though somewhat elongated, they do not have the extreme egg shape characterizing the gastrula of *Echinarachnius mirabilis* as figured by Mortensen (1921).

The body of the four-armed larva at 46 hours is supported by a skeleton as shown in Figure 23. The postoral rods are fenestrated, while the anterior lateral rods are solid and more or less thorny. The distal or posterior ends of the recurrent and body rods are irregularly branched and, in later four-armed specimens, are fused at their tips to form a perforated basket-like structure which is characteristic of the clypeasteroid larva.

About the sixth day the third pair of arms, i.e., the posterodorsal arms, appeared, together with their fenestrated supporting rods. Mortensen was of the opinion that these rods were articulated with the main skeletal structure, but our observations indicate that they are freely suspended in the tissue with no regular contact with other skeletal parts. The posterior portion of these rods is solid and branched. One branch elongates to become the dorsal transverse rod which supports the dorsal larval tissue (Figs. 24 and 26).

At this time the dorsal arch, destined to become the supporting rods for the preoral arms, appears as a small triradiate spicule in the dorsal tissues near the mouth. The preoral arms are already indicated by small knobs.

In some specimens the external ventral transverse rods may appear as early as the sixth day, but often do not appear until the other larval skeletal structures have been fully formed. These belated rods are usually smoother than the earlier inner transverse rods. They are deflected outward to support the tissues posterior to the anus (Fig. 25).

The earliest appearance of the echinus rudiment (marking the beginning of metamorphosis) was 10 to 15 days. It is of interest to note that several specimens formed twin or double echinus rudiments, one on each side of the stomach. This strange irregularity has been observed before in the pluteus larva of *Mellita pentapora* and made the subject of a paper by Grave (1911), who states, "It shows no doubleness whatever in its purely *larval* organization and can only be viewed as *one* individual, although *twin* sand dollars or a double monster would have been the result of its final metamorphosis." Grave worked on a single preserved specimen, hence the result of metamorphosis was not observed. None of our specimens is known to have lived through metamorphosis.

The anterior ciliated epaulettes were formed by detachment from the ciliated band at about 45 days (Fig. 27). No posterior epaulettes, such as occur in *Strongylocentrotus franciscanus,* were developed.

Many specimens of the 1933 culture proceeded to an advanced stage of metamorphosis with partial or almost complete absorption of the arms at 50 to 70 days, but only three specimens completed metamorphosis to young sand dollars (Fig. 28). Only the external features of these were studied.

The little animal at 87 days is about 0.3 mm. in diameter, is covered aborally with irregular patches of calcareous plates and spicules imbedded in the tissues. These plates were formed into five indistinct groups which no doubt represent a beginning of the five genital plates. Around the periphery and extending to the oral side, the calcareous plates formed a rather continuous structure with projecting tubercles upon which the spines are articulated. The spines at this age are of three types: (a) short conical spines; (b) large club-shaped spines; and (c) somewhat longer, more cylindrical spines, of which there were only two, situated side by side at the narrower end of the long axis of the animal. The distribution of the spines is shown in Figure 28, from which it is seen that the young animal is already slightly oval and bilaterally symmetrical, with one long spine on either side of the mid-line along the main axis. The five teeth of the Aristotle's lantern were plainly visible under the skin, but no pedicellariae could be found. The animals were very active, moving about with the aid of the longer spines and long primary tube feet, which could be extended beyond the end of the longest spines. The cultures were of necessity terminated at the end of 87 days.

Summary

1. *Cucumaria chronhjelmi* and certain other holothuroidean larvae were studied from specimens secured from the plankton during the months of March, April, May, and June. They were cultured for two periods of ten months each during two successive years.
2. Data secured would indicate that spawning is more or less synchronous for a large population. *C. chronhjelmi, C. miniata, C. piperata, Psolus chitonoides*, and *Stichopus californicus* spawn during the spring months.
3. Diatoms, especially *Nitzschia* and *Navicula,* were found to be valuable as food for the larvae.
4. The larva studied in detail was identified as *C. chronhjelmi.* Its development was found to be similar to that of other species of *Cucumaria* studied elsewhere. Specimens reared from the embryo developed directly into Doliolaria larvae, there being no auricularian stage.
5. Other larvae tentatively identified were those of *C. piperata, C. populifera,* and *C. miniata.*
6. The green embryos and larvae found in the spring plankton are mainly *C. chronhjelmi,* and the orange-colored embryos and larvae are perhaps mainly *C. miniata.*
7. *Dendraster excentricus* was reared from artificially fertilized eggs through metamorphosis. The first set of cultures was from artificially fertilized eggs, the sex products being taken from the adults in June 1931. A second set of cultures was set up in September 1933 from specimens spawning spontaneously in the laboratory. The pluteus larvae are of the clypeasteroid type. They metamorphosed in 60 to 85 days.

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PLATE I

Figures 1–6. *Cucumaria chronhjelmi*

Fig. 1. Blastula

Fig. 2. Early gastrula

Fig. 3. Doliolaria larva—ventral view

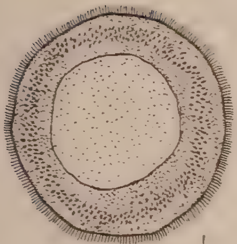
Fig. 4. One-week-old larva—dorsal view

Fig. 5. Flattened larva to show ventral canal, etc.

Fig. 6. Twenty-one-day larva—dorsal view, to show regular arrangement of body plates

Explanation of labels

at—atrium
hp—hyaline papilla
p_1—primary pedicil
pdt—primary dorsal tentacle
pvt—primary ventral tentacle
t—tentacle
vrc—ventral radial canal



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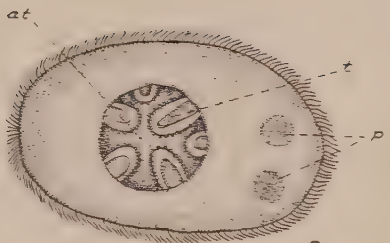

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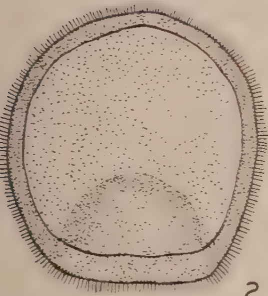

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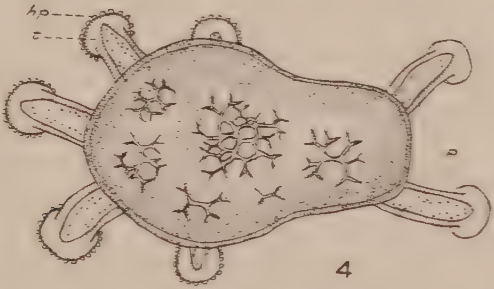

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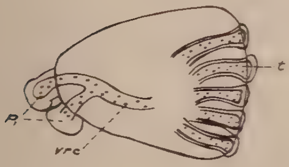

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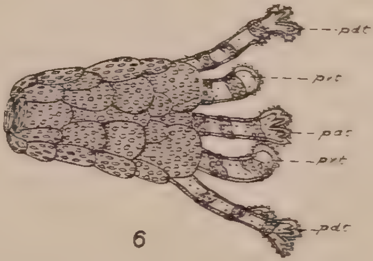
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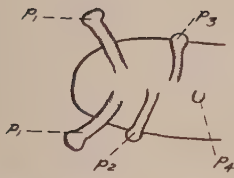
PLATE II

Figures 7–14 and 17. *Cucumaria chronhjelmi*
Figure 15. *C. piperata* (?)
Figure 16. *C. populifera* (?)

Fig. 7. Ventral view, showing arrangement of pedicils
Fig. 8. Specimen nine weeks old
Fig. 9. Oral view, showing position of first pair of secondary tentacles
Fig. 10. Oral view fourteen weeks old
Fig. 11. Specimen fourteen weeks old
Fig. 12. Plates from calcareous ring of young *C. chronhjelmi*
Fig. 13. Plates from calcareous ring of ten-month-old specimen
Fig. 14. Body plates of adult *C. chronhjelmi*
Fig. 15. Plates from tentacle of *C. piperata* larva
Fig. 16. Plate from body of *C. populifera* larva
Fig. 17. Tentacular plates of adult *C. chronhjelmi*

Explanation of labels

dpt—dorsal primary tentacle
lpt—left primary tentacle
p_1—primary pedicil
p_2—first secondary pedicil
p_3—second secondary pedicil
p_4—third secondary pedicil
rpt—right primary tentacle
st_1—first secondary tentacle
st_2—second secondary tentacle
st_3—final secondary tentacle
vpt—ventral primary tentacle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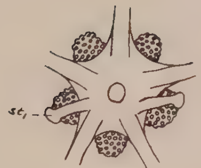

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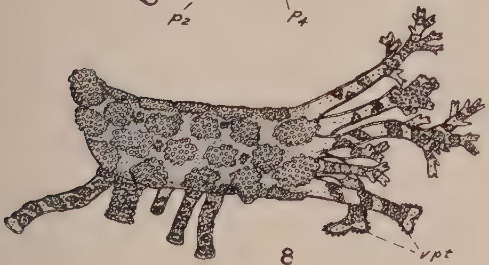

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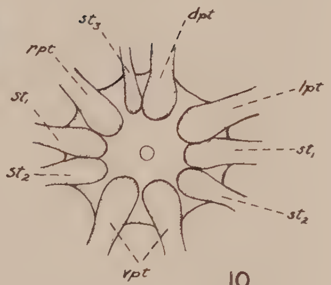
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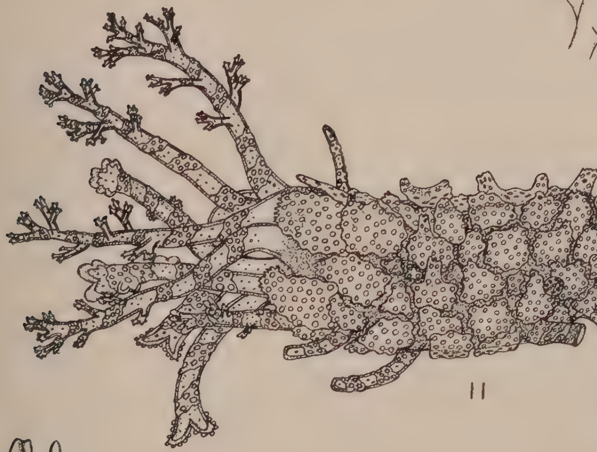

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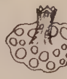

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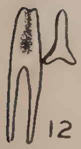

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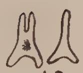

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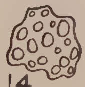

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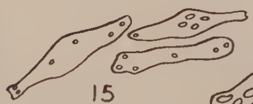

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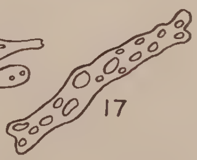

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PLATE III

Figures 18–27. *Dendraster excentricus*—Larval development

Fig. 18. Two-cell stage—20 minutes

Fig. 19. Beginning 4-cell stage—50 minutes

Fig. 20. Four-cell stage—60 minutes

Fig. 21. Blastula—8 hours

Fig. 22. Gastrula—24 hours

Fig. 23. Four-armed larva—46 hours ventral, complete skeleton

Fig. 24. Early 8-armed larva—6 days ventral, complete skeleton

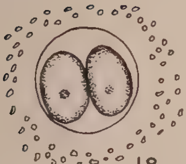
Fig. 25. Eight-armed larva—21 days ventral, to show ventral skeleton only

Fig. 26. Eight-armed larva—21 days dorsal, to show dorsal skeleton

Fig. 27. Forty-nine-day metamorphosing larva—ventral, only ventral larval skeleton shown

Explanation of labels

ala—anterior lateral arm
alr—anterior lateral rod
b—calcareous basket
br—body rod
ce—ciliated epaulettes
cs—calcareous star
da—dorsal arch
dtr—dorsal transverse rod
er—echinus rudiment
ovtr—outer ventral transverse rod
pda—postero-dorsal arm
pdr—postero-dorsal rod
poa—postoral arm
por—postoral rod
s—larva stomach
vi—vibratile lobes
vtr—ventral transverse rod



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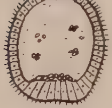

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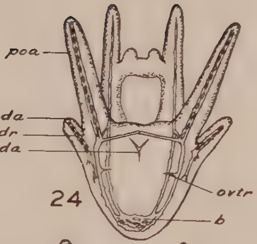
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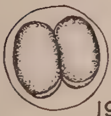

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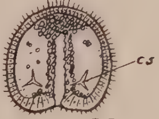

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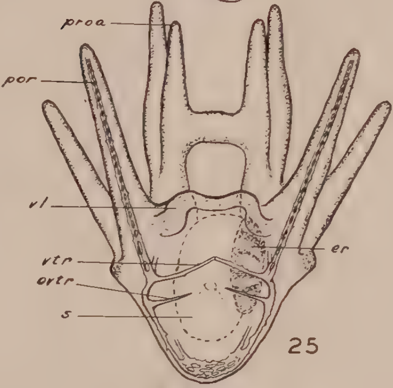
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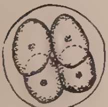

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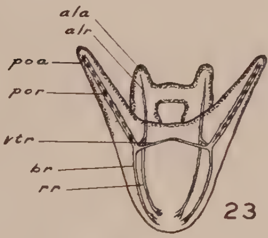
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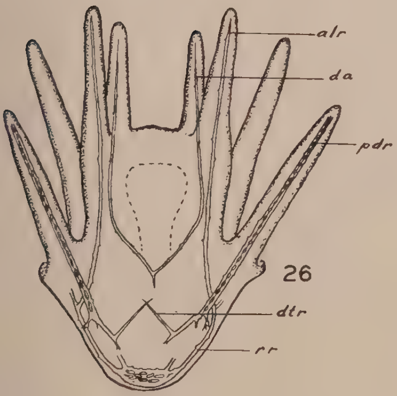
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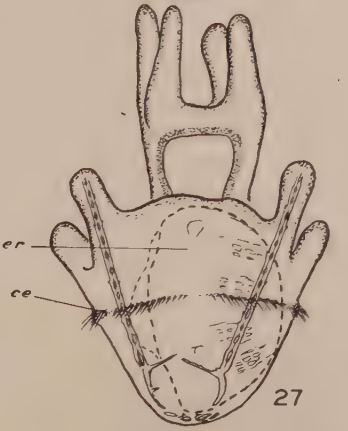

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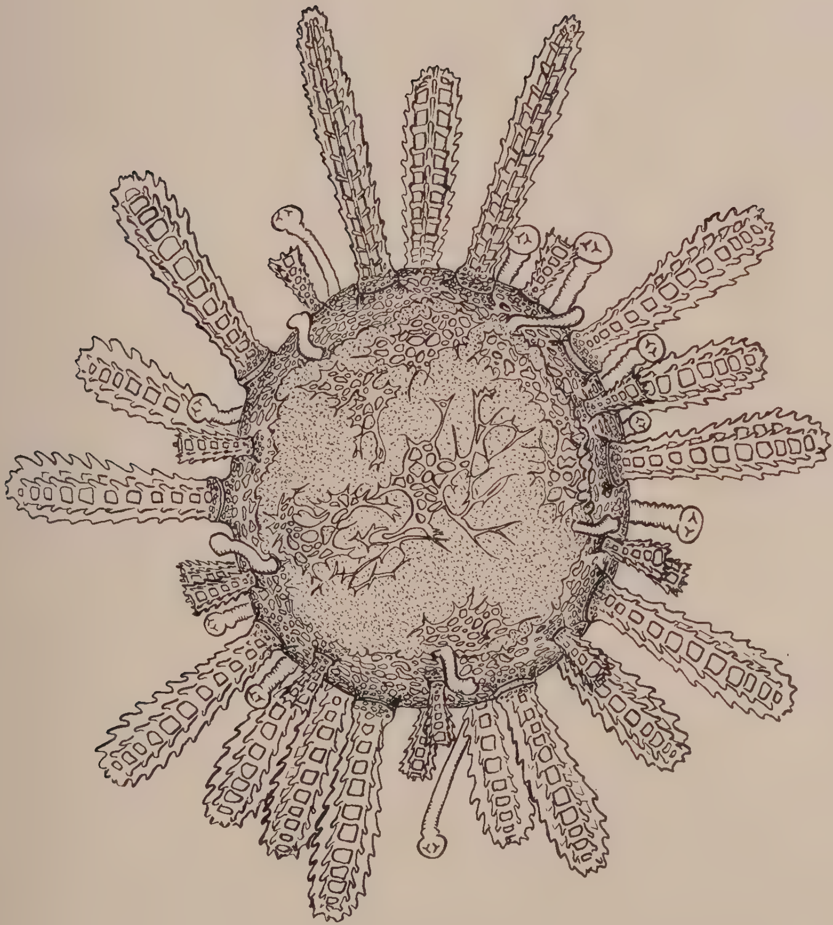
PLATE IV

Figure 28. *Dendraster excentricus*—young sand dollar—86 days old



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Contribution No. 440

Nicht im Handel

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(Scripps Institution of Oceanography[1], University of California.)

The Distribution and some Effects of the Seasonal uantities of E—P (Evaporation minus Precipitation) over the North Atlantic and North Pacific.

By

Woodrow C. Jacobs,
Headquarters, Air Weather Service, Washington D. C.

With 6 Figures.

Summary. In connection with an investigation of the energy relations etween sea and atmosphere, two by-products were a set of seasonal precipi- tion charts for all oceans and a set of seasonal evaporation charts for the orth Atlantic and North Pacific oceans. These data have made possible the etermination of the important seasonal and annual values of $E-P$ for the tter two areas. Some of the more important conclusions drawn from these mputations are that:

1. The $E-P$ values over the North Atlantic and North Pacific are nearly erywhere greatest in winter and least in summer.

2. The largest positive values of $E-P$ occur in the subtropical regions uring all seasons, with secondary areas of maximum $E-P$ during one or ore of the cooler seasons in the western portions of the oceans south of titude 40° N. Large negative values occur in the equatorial regions and at gh latitudes in the northeastern portions of both oceans throughout the year.

3. The total excess of evaporation over precipitation is, in both oceans, uch greater in winter than in summer. In fact, the total precipitation over oth oceans during summer exceeds the total evaporation, indicating that the orthern Hemisphere oceans are not sources of moisture for precipitation er land during that season.

4. Through the use of Wüst's formulae, which show the relation between e zonal values of the surface salinity and the zonal values of the annual $-P$, an annual chart of the computed surface salinities has been prepared. n additional difference chart of the observed minus the computed salinities r the North Atlantic and North Pacific indicates that there is a tendency r the areas of maximum (or minimum) surface salinities to be displaced *um sole*) in the direction of surface flow away from the areas of maximum r minimum) $E-P$.

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[1] Contribution No. 440, New Series.

5. A plot (on an equal-area scale) of the average zonal values of th observed minus the computed salinities indicates that the positive areas o the preceding difference chart very nearly equal in extent the negative area in the North Pacific, but that, in the North Atlantic, the positive area (regions showing importation of high salinity water) greatly exceed the negativ areas in extent. If the difference values are taken to be approximatel correct, this result implies that considerable high salinity water must b advected into the North Atlantic across the Equator from the South Atlanti

Zusammenfassung. Im Zusammenhang mit einer Untersuchung über d energetischen Beziehungen zwischen Meer und Atmosphäre wurden als Neben ergebnisse eine Serie von jahreszeitlichen Niederschlagskarten für alle Ozean und eine Serie von jahreszeitlichen Verdunstungskarten für den Nordatlan tischen und den Nordpazifischen Ozean aufgestellt. Dadurch wurde für die zwei Gebiete die Bestimmung der wichtigen Werte von $E-P$ (Verdunstung Niederschlag) für die Jahreszeiten und das Jahr ermöglicht. Die wichtigste Folgerungen aus diesen Berechnungen sind:

1. Die $E-P$-Werte über dem Nordatlantischen und dem Nordpazifische Ozean sind fast überall am größten im Winter und am kleinsten im Somme

2. Die größten positiven Werte von $E-P$ finden sich in allen Jahreszeite in den subtropischen Gebieten mit sekundären Maxima während einer ode mehrerer kühlerer Jahreszeiten in den westlichen Teilen der Ozeane südlic von 40° N. Große negative Werte von $E-P$ treten während des ganzen Jahre in den Äquatorialgebieten auf sowie unter hohen Breiten in den nordöstliche Gebieten beider Ozeane.

3. Der gesamte Überschuß der Verdunstung über den Niederschlag ist i beiden Ozeanen im Winter viel größer als im Sommer. Der gesamte Niede schlag über beiden Ozeanen übersteigt im Sommer tatsächlich die gesamt Verdunstung, woraus hervorgeht, daß die Ozeane der Nordhemisphär während dieser Jahreszeit nicht Feuchtigkeitsquellen für den Niederschla über dem Lande sind.

4. Unter Benützung der Formeln von WÜST, die eine Beziehung zwische den Zonenwerten des Oberflächensalzgehalts und den jährlichen Zonenwerte von $E-P$ geben, wurde eine Jahreskarte der berechneten Oberflächensalz gehalte aufgestellt. Eine weitere Karte der Differenzen zwischen den beob achteten und den berechneten Salzgehalten des Nordatlantik und des Nord pazifik läßt erkennen, daß für die Gebiete maximalen (bzw. minimalen) Ober flächensalzgehalts die Tendenz besteht, sich im Uhrzeigersinn in der Richtun der Oberflächenströmung von den Gebieten maximaler (bzw. minimaler Werte von $E-P$ hinweg zu verlagern.

5. Ein Diagramm mit flächentreuer Skala mit den mittleren Zonenwerte der Differenzen zwischen beobachteten und berechneten Salzgehalten läß erkennen, daß die positiven Gebiete der vorangehenden Differenzkarte in Nordpazifik fast genau gleich groß sind wie die negativen Gebiete, daß da gegen im Nordatlantik die positiven Gebiete (mit Zufluß von Wasser mi hohem Salzgehalt) die negativen Gebiete an Ausdehnung stark übertreffen Nimmt man an, daß die Differenzwerte annähernd richtig sind, so folgt daraus daß ein beträchtlicher Zufluß von Wasser mit hohem Salzgehalt vom Süd atlantik über den Äquator zum Nordatlantik stattfinden muß.

Résumé. En marge de recherches sur les relations énergétiques entre l mer et l'atmosphère, nous avons dressé une série de cartes saisonnières de

récipitations pour tous les océans ainsi que des cartes saisonnières de l'éva- oration pour l'Océan Atlantique nord et l'Océan Pacifique nord. Ces docu- ents rendirent possible la détermination par saison et par année de la randeur importante $E-P$ (évaporation — précipitations). Les conclusions écoulant de ces calculs sont les suivantes.

1. Les valeurs de $E-P$ pour l'Atlantique nord et le Pacifique nord sont resque partout maxima en hiver et minima en été.

2. Les plus grandes valeurs positives de $E-P$ se rencontrent en toutes isons dans les régions subtropicales avec des maxima secondaires lors d'une u de plusieurs saisons froides dans les parties occidentales de ces océans, au ud de 40° N. De fortes valeurs négatives de $E-P$ apparaissent pendant oute l'année dans les régions équatoriales ainsi que sous les hautes latitudes ans les parties Nord-Est des deux océans.

3. L'excédent total d'évaporation sur les précipitations est beaucoup plus ort en hiver qu'en été dans les deux océans. Les précipitations totales emportent en fait en été sur l'évaporation, d'où il suit que les océans de hémisphère nord ne sont pas en cette saison des sources d'humidité pour s pluies continentales.

4. On a dressé une carte des valeurs annuelles de la salinité des eaux perficielles en utilisant les formules de WÜST qui fournissent une relation ntre la salinité zonale et les valeurs zonales annuelles de $E-P$. Une carte ontenant les différences entre les salinités observées et calculées de l'Atlan- que nord et du Pacifique nord montre que les régions à salinité superficielle aximum (ou minimum) ont tendance à s'écarter dans le sens direct des gions à valeur maximum (ou minimum) de $E-P$ dans la direction des ourants de surface.

5. Un diagramme à échelle à surfaces conformes des valeurs moyennes onales des différences entre les salinités observées et calculées montre que s régions positives de la carte précédente sont presque de même étendue ans le Pacifique nord que les régions négatives, mais que par contre dans Atlantique nord les régions positives (alimentées par de l'eau plus salée) sont ettement plus étendues que les régions négatives. Si l'on admet que les fférences en question sont à peu près exactes, il s'ensuit qu'un apport portant d'eau à forte salinité a lieu de l'Atlantique sud vers l'Atlantique nord.

I. Introduction.

Some results of an investigation on the energy exchange between sea id atmosphere have already been published (JACOBS, 1942 and 1943) gether with seasonal charts of evaporation rates over the North Atlantic id North Pacific. More recently the author has prepared seasonal recipitation charts for all oceans (JACOBS, 1948 a). The existence of iese two sets of data permits the determination of the important seasonal id annual values of $E-P$ for the North Atlantic and North Pacific. his information is of oceanographic interest to the extent that the fference between evaporation and precipitation (through the control of irface salinities) is a factor, in addition to surface heating and cooling, iat serves to alter the distribution of density in the oceans. The data re of meteorological interest to the extent that they identify the principal ceanic sources of moisture that enters into precipitation over the land irfaces of the Northern Hemisphere.

II. The Seasonal and Annual Values of *E–P* for 10-Degre Squares in the North Atlantic and North Pacific.

It is not practicable to include all of the seasonal charts and th annual chart of *E–P* in the present short paper. However, the winte and summer charts ar given as figures 1 and 2 The outstanding feature of the *E–P* charts ar the large positive value that occur in the subtropical regions and th large negative values tha occur in the equatoria regions and in high latitudes in the northeaster portions of both ocean Secondary areas of maximum *E–P* occur in th western portions of th oceans south of latitud 40° N., during the coole seasons in the North Atlantic and during winte in the North Pacific There is, in addition during winter a thir area of maximum *E–P* in the northern Nort Atlantic, centered slightl west of the 40th meridian and north of latitud 40° N. In the easter North Pacific, the horizontal difference betwee the annual *E–P* at the Equator and that in latitude 20° N., is of the order of 180 cms; an in the Atlantic, of the northeast coast of Sout America, it is of the order of 150 cms withi the same latitude range

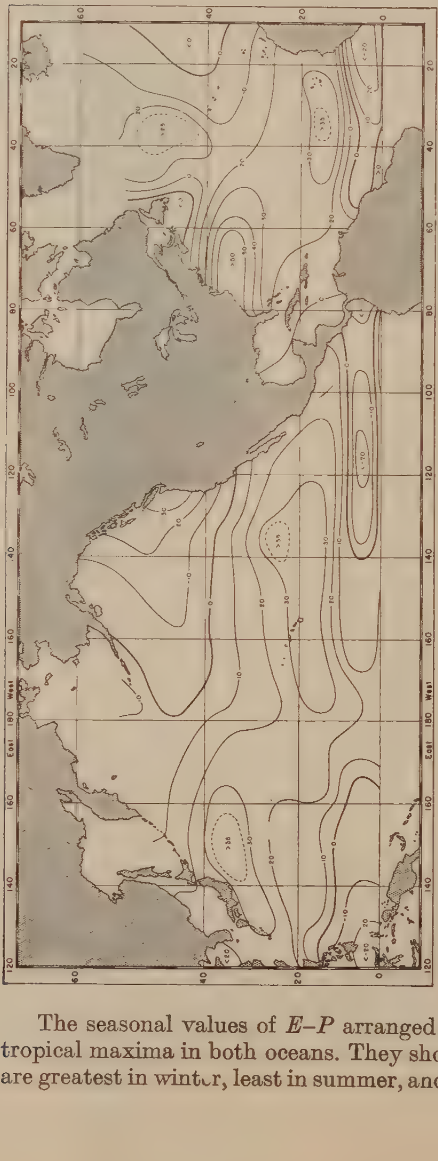


Fig. 1. Mean values for *E–P* over the North Atlantic and North Pacific during winter (Dec., Jan., Feb.) expressed in cms/season.

The seasonal values of *E–P* arranged according to latitude show subtropical maxima in both oceans. They show, further, that the *E–P* values are greatest in winter, least in summer, and, in all seasons, negative south o titude 10° N. and north of latitude 45° N. except in the North Atlantic, here the winter values are positive everywhere north of the 10° N. parallel.

Albrecht (1947) has recently prepared a rough annual chart showing e annual $E-P$ over the oceans based upon comparisons between obser-ed surface salinities nd those computed by eans of Wüst's (1936) rmulae which give the rface salinities as a nction of $E-P$, a ethod which will be scussed in greater de-il in the last section.

A comparison of Al-recht's annual chart nd the one prepared om the evaporation nd precipitation data ows that the two ree in the gross fea-res. Both show large eas of maximum $E-P$ the subtropics with eir long axes orien-d approximately east-est. However, in the orth Pacific, Albrecht aces the center of the aximum along the 0th meridian at about titude 20° N. The thor's chart, on the her hand, shows the nter to be located nsiderably farther stward at longitude 5° W. and latitude ° N. In the North At-ntic, Albrecht places e center of the maxi-um area along the 40th eridian at about lati-de 20° N., while the thor's chart shows this area to be located at 45° W. und 15° N. ubsequent discussion will show that this displacement of the centers ould be expected on the basis of the horizontal circulation which tends shift the areas of maximum surface salinity away from the areas of

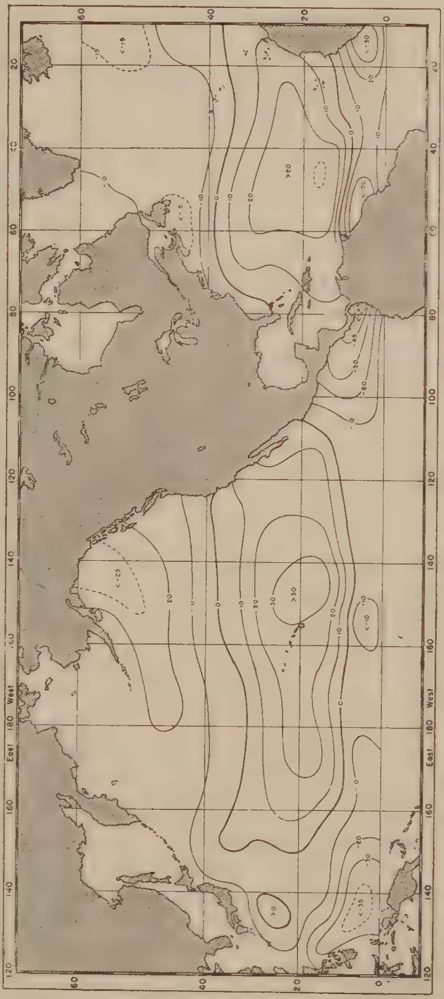


Fig. 2. Mean values for $E-P$ over the North Atlantic and North Pacific during summer (June, July, Aug.) expressed in cms/season.

maximum $E-P$. WÜST's formulae apply regionally only in the absenc of significant horizontal transport. Therefore, any $E-P$ chart base upon an examination of the distribution of surface salinities can, a best, be only a rough approximation.

III. The Thermohaline Circulations.

A few remarks are perhaps in order relative to the haline and therma circulations which result from the regional differences in heating an cooling and $E-P$, even though the forces created are relatively unimpor ant as far as their effects upon the general horizontal circulations of th oceans are concerned.

If $E-P$ were the only factor serving to determine the distribution c density in the oceans, the distribution would be altered in such a fashio that the isosteric surfaces would, in general, slope upward toward th centers of maximum $E-P$ in each ocean, the magnitude of the slope bein proportional to the horizontal gradients of $E-P$. The final result woul be the development of weak cyclonic haline circulations in the surfac layers about each of the centers of maximum $E-P$. The haline circula tions resulting from the regional differences in $E-P$ would thus tend t oppose the general anticyclonic wind circulations which exist in the tw oceans. The accompanying north-south circulation would, at the surfac be directed from regions of negative values of $E-P$ to regions of positiv values.

The differential heating and cooling of the ocean surfaces would, i general, create a surface flow from low to high latitudes. Thus the nortl south circulations arising from the heating at the Equator and the relativ cooling in the higher latitudes would augment the haline circulations i the regions between the subtropics and high latitudes.

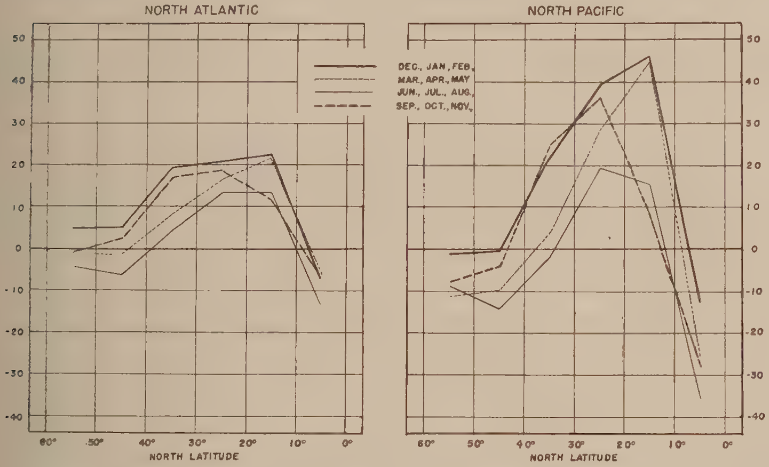
Because of the relative unimportance of these processes in determinin the general horizontal circulations of the oceans, no attempt will be mad to deal with them in a quantitative manner.

IV. The Total Excess of Evaporation over Precipitation in th North Atlantic and North Pacific.

The seasonal values of the total excess of evaporation over precipita tion are given in figure 3. These curves show that the principal ocean source of moisture for precipitation over land is the subtropical ocea area. The equatorial regions do not contribute during any season, nor d the latitudes higher than 45° contribute anywhere except in the Nort Atlantic during the winter season.

As shown by the data in table 1, the seasonal variations in $\Sigma(E-I$ are greater in the North Pacific than in the North Atlantic. This i exactly opposite in the case of evaporation (see JACOBS, 1943).

To obtain some idea of the magnitude of the seasonal totals of $\Sigma(E-I$ given in Table 1, and of their possible importance to the water econom f the two oceans, it is convenient to compare the quantities with the olumes of water transported by ocean currents. If it could be assumed hat the North Atlantic Ocean were closed everywhere except through he Straits of Florida, the computed $\Sigma(E-P)$ quantities (neglecting the ffects of run-off from land surfaces) would require the following compensating flows through the Straits in order that there be no change in ea-level:



ig. 3. Seasonal values of the total evaporation minus precipitation, $\Sigma(E-P)$, for the North Atlantic and North Pacific.

Winter	0,76	million	m³/sec	Inflow
Spring...........	0,43	,,	,,	,,
Summer	0,07	,,	,,	,,
Autumn	0,47	,,	,,	,,
Year	0,43	,,	,,	,,

These values may be compared to the actual transport through the traits of Florida which is approximately 26 million m³/sec., and to the ransport within the Gulf Stream off the east coast of the United States hich averages approximately 80 million m³/sec.

It should be mentioned that the seasonal totals of $\Sigma(E-P)$ for the orth Atlantic do not include the totals for the Mediterranean Sea, the lack Sea or the Arctic Mediterranean Sea[1], all of which are tributary to the North Atlantic. However, according to data given by Sverdrup (1942), the annual excess of precipitation over evaporation in the Arctic Mediterranean is about 2,84 × 10^{12} m^3/year. This amount is almost exactly balanced by the excess of evaporation over precipitation that occurs within the Black Sea and the Mediterranean Sea where the total $\Sigma(E-P)$ is about 2,77 × 10^{12} m^3/year[1]. This would indicate that the annual total excess of evaporation over precipitation for the North Atlantic given above should be approximately correct for the entire Atlantic Basin area north of the Equator.

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[1] The Arctic Mediterranean includes the North Polar Sea, the waters of ne Canadian Archipelago, Baffin Bay, and the Norwegian Sea, and is erefore separated from the open Atlantic by a line joining Labrador and reenland in Davis Strait and running through Greenland, Iceland, Faeroe slands, Scotland, and England, and across the English Channel to the ontinent (SVERDRUP, l. c.).

Table 1. *Means of the Total Daily Evaporation minus Precipitation Deficit [$\Sigma(E-P)$] over the North Pacific and North Atlantic.*

Area	Season	Mean $\Sigma(E-P)$ 10^6 m^3/day	$\Sigma(E-P)$ for both oceans per cent	Mean Annual $\Sigma(E-P)$ per cent
North Pacific	Winter	93 542,3	58,8	73,9
	Spring	30 174,3	44,8	23,9
	Summer	— 26 290,5	130,1 (of deficit)	— 20,8
	Autumn	29 033,8	44,3	23,0
	Year	31 615,0	45,8	100,0
North Atlantic ...	Winter	65 627,3	41,2	43,8
	Spring	37 110,0	55,2	24,8
	Summer	6 075,0	— 30,1 (of deficit)	4,1
	Autumn	40 875,5	55,7	27,3
	Year	37 422,0	54,2	100,0
Both Oceans	Winter	159 169,6	100,0	57,6
	Spring	67 284,3	100,0	24,4
	Summer	— 20 215,5	100,0	— 7,3
	Autumn	69 909,3	100,0	25,3
	Year	69 037,0	100,0	100,0

Total Annual $\Sigma(E-P)$:

North Pacific
= 11 539,5 × 10^9 m^3/year: equivalent to a mean depth of 14,2 cms/year,
North Atlantic
= 13 659,0 × 10^9 m^3/year: equivalent to a mean depth of 34,5 cms/year,
Both Oceans[2]
= 25 198.5 × 10^9 m^3/year: equivalent to a mean depth of 20,8 cms/year.

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[1] These totals were estimated from an examination of the differences between salinities of outflowing and inflowing waters.

[2] This value can be considered to represent the total $\Sigma(E-P)$ over all Northern Hemisphere oceans except the Red Sea and that portion of Indian Ocean north of the Equator. This is true because the negative $\Sigma(E-P)$ of the Arctic Mediterranean almost exactly balances the positive combined $\Sigma(E-P)$ of the Mediterranean and Black Seas.

If the same reasoning is applied to the North Pacific, that is, if it is ssumed that the North Pacific is closed everywhere except, say, through he Bering Straits, the differences between evaporation and precipitation ould require the following compensating flows through the Straits:

Winter	1,08 million m^3/sec	Inflow
Spring............	0,35 ,, ,,	,,
Summer	0,30 ,, ,,	Outflow
Autumn	0,34 ,, ,,	Inflow
Year	0,37 ,, ,,	,,

These figures are interesting in that they show in summer (when there s an excess of precipitation over evaporation) an outflow through the Straits which would be due to the annual excess of evaporation over recipitation.

For purposes of comparison, it may be pointed out that the actual ransport of the Pacific Equatorial Counter Current is about 25 million m^3/sec. in mid-Pacific, that of the Kuroshio is about 45 million m^3/sec., hile the transport of the relatively wide but sluggish California Current s about 10 million m^3/sec.

As shown in table 1, the total annual $\Sigma(E-P)$ in the North Atlantic s of the order of 14×10^{12} m^3/year which is equivalent to a mean depth f about 34,5 centimeters per year. The total $\Sigma(E-P)$ over the North acific, on the other hand, is only $11{,}5 \times 10^{12}$ m^3/year which is equivalent o a mean depth of approximately 14 centimeters per year. Only during inter does the $\Sigma(E-P)$ of the North Pacific exceed that of the North tlantic. *Thus, in spite of its greater area, the North Pacific actually ontributes less moisture for precipitation over land than does the North tlantic.*

The total annual excess of evaporation over precipitation for both ceans is of the order of 25×10^{12} m^3/year which is equivalent to a mean epth of approximately 21 centimeters per year. Because the excess recipitation of the Arctic Mediterranean almost exactly balances the xcess evaporation of the Black Sea and Mediterranean Sea, this figure an be considered to represent all the Northern Hemisphere oceans with he exception of the Red Sea and the portions of the Indian Ocean north f the Equator. It is to be expected that these latter two areas will also end to balance one another. Evaporation figures are not available for he Indian Ocean, but because of the great amount of precipitation in his area it is to be expected that precipitation will greatly exceed evaporaion as far as the annual total is concerned. In the Red Sea, on the other and, it is to be expected that evaporation greatly exceeds precipitation s indicated by the high surface salinities. VERCELLI (1925) estimates that he evaporation in the Red Sea is approximately 3,5 meters per year hich, because of the low amount of precipitation would give an annual xcess of evaporation over precipitation greater than 3 meters. However, ERCELLI's results may be doubtful since he has based his computations upon pan measurements made at shore stations. He concludes, for example, that the evaporation in this area is greater in summer than in winter. This conclusion is based on the assumption that the annual variation of evaporation over land is the same as the annual variation over an extensive sea surface which is obviously incorrect. It is to be expected that in the Red Sea winter evaporation will exceed summer evaporation as it does in other ocean areas similarly located.

Neglecting for the moment the transport of water vapor across the Equator, the figure of 25×10^{12} m^3/year should approximately equal the excess amount of water available for precipitation over land. By the same reasoning, this amount should also equal the total run-off from all land areas in the Northern Hemisphere, for it can be assumed that the oceans are neither gaining nor losing mass. However, due to the transport of water vapor across the Equator, particularly by the Asiatic Monsoon Current of northern summer, it is to be expected that the total moisture available from the oceans for precipitation over the land surfaces of the Northern Hemisphere will be somewhat greater.

The data in table 1 show that, *in summer, the Northern Hemisphere oceans are not sources of moisture for precipitation over land.* The total excess of precipitation over evaporation of approximately 20×10^9 m^3/day means either that this amount is supplied by excess evaporation over the continents or that this amount is transported across the Equator from the winter hemisphere. It is suggested that both conclusions are true. It is known that evaporation over land surfaces is at a maximum during summer, although it has not been known that the total excess over precipitation exceeds that of the oceans during this season. It is also probable, as has been indicated, that considerable water vapor is transported northward across the Equator during the northern summer months, particularly within the Asiatic monsoon streams of the Indian Ocean and southwestern North Pacific.

Table 2. *Seasonal Ratios between Total Daily Evaporation minus Precipitation Deficit $\Sigma(E-P)$ in the North Pacific and North Atlantic Oceans.*

Season	Ratio $\frac{\Sigma(E-P)\ (\text{N. Pacific})}{\Sigma(E-P)\ (\text{N. Atlantic})}$
Winter	1,43
Spring	0,81
Summer	— 4,33
Autumn	0,71
Year	0,84

BYERS (1944) has noted that, in summer, the surfaces of the average potential temperature over the Pacific off the North American coast slope upward toward the west; and from this fact he concludes that the North Pacific cannot act as an important source of moisture for precipitation over North America during this season. This verifies, in part, the similar conclusion arrived at in this section on the basis of the $\Sigma\,(E-P)$ values and as shown by table 1.

The seasonal ratios between the $\Sigma\,(E-P)$ values in the North Pacific and North Atlantic are given in table 2 which quantitatively illustrates he wide seasonal variations in this quantity between the two oceans.

V. Relations between the Annual Regional Values of E—P and Surface Salinities over the North Atlantic and North Pacific[1].

In the absence of horizontal flow, the surface salinity of any part of he ocean would be mainly determined by three processes: Decrease of alinity by precipitation, increase of salinity by evaporation, and change of salinity by vertical mixing. In general, we should expect the regions where E–P is large to be also regions of high surface salinities and the egions where E–P is small, or negative, to be regions of low surface alinities. However, horizontal flow is also important in determining the egional salinity, and acts towards displacing the areas of maximum (or minimum) salinity in the direction of surface flow away from the areas of maximum (or minimum) E–P.

Wüst (1936) has found that the average annual surface salinities can be related to the average annual latitudinal values of E–P quite accurately by a simple empirical expression of the form:

$$S_0 = K\,(E-P) + S_K, \tag{1}$$

where S_0 is surface salinity, K is a constant, S_K is a constant salinity, and E–P is given in cm/year. He finds it necessary, however, to assign different values for K and S_K for the several oceans. His values for K range from 0,0170 in the North Atlantic between latitudes 25° N. and 40° N. to 0,0179 in the Atlantic area between 50° S. and 20° N. His values for S_K range from a low value of $33{,}70^0/_{00}$ for the Pacific area between 15° N. and 40° N. to a high value of $35{,}30^0/_{00}$ for the Atlantic area between 25° N. and 40° N. His formulae do not apply near the coasts where the horizontal transport term tends to be large and where the effects of run-off from land surfaces may be important. They also do not apply near the Equator.

Through the use of Wüst's formulae which apply to the North Pacific and North Atlantic it is possible, on the basis of the established annual E–P values, to prepare a salinity chart which, in at least a semi-quantitative manner, will show the distribution of the annual surface salinity as it would exist in the absence of an oceanic circulation. As has just been pointed out, Wüst's formulae are not intended to apply near the coasts, where run-off could be important, nor do they appear to give good results near the Equator. Furthermore, WÜST gives radically different values for S_K for the areas north of latitude 20° N. in the Atlantic and 15° N. in the Pacific than in the areas of the two oceans between these latitudes and the Equator. Thus a marked discontinuity is forcibly introduced within these latitude ranges. In view of these uncertainties it was to be expected that the computed absolute salinities would show some error. However, as will be indicated in the subsequent discussion of the results, the computed values appear to be surprisingly reliable.

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[1] Some empirical relations between seasonal values of E–P and surface alinities over selected areas in the North Atlantic have been presented in a separate paper (Jacobs, 1948 b).

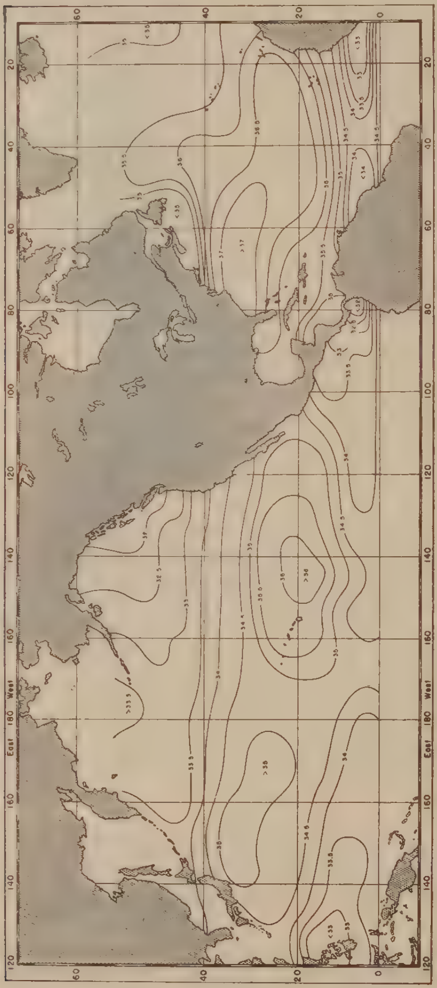

Fig. 4. Distribution of the computed annual salinities (S_0) over the North Atlantic and North Pacific.

The result of the computations[1] are given in figure 4. As would be expected, the configuration of isolines is quite similar to the configuration of isolines on the annual $E-P$ chart from which they have been derived. The North Pacific shows two centers of maximum salinity, one centered along the 20th parallel in the eastern North Pacific and another centered along the 30th parallel in the western North Pacific. Centers of low salinity exist within the equatorial regions in the eastern and western portions of the orth Pacific with a third very pronounced region of low salinity water ong the western coast of Canada.

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[1] In all cases where the computed annual salinities are compared with the observed salinities, it has been necessary to use the observed summer (or July) salinities due to the lack of data concerning the average annual salinities for the Pacific. The error introduced by this substitution should not be significant although, for the oceans as a whole, the summer salinities are probably slightly lower than the annual salinities due to the small $E-P$ during summer.

In the North Atlantic the center of the single area of maximum linity is located just north of latitude 30° N. and near the American ast. Two centers of inimum salinity exist the Equatorial region, ie along the South merican coast and iother along the Afri- n coast. Two other gions of low salinity ist in the northeastern id northwestern North tlantic.

In order to give some cture of the effects horizontal transport oon surface salinities, a fference chart showing e observed minus the mputed salinities has en prepared and is ven as figure 5. This art shows that there e large areas where gh salinity water is ing advected in the uthwestern, central, id northwestern por- ons of the two oceans, id that there are large eas where low salinity aters are being ad- cted in the north- estern portions of both eans. There exists, in ldition, in the eastern id southeastern part the North Pacific, a rge area where low linity water is being lvected. These results e in line with our knowledge of the surface circulations of these two eans. In the North Pacific there is a general clockwise migration of e areas of maximum and minimum surface salinities away from the eas of maximum and minimum *E–P* which is in accordance with

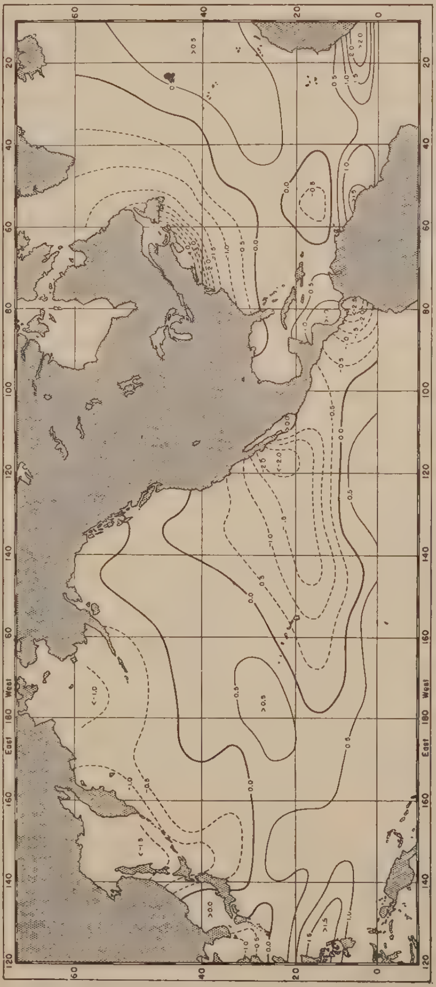

Fig. 5. Distribution of the observed summer (S) minus the computed annual (S_0) salinities over the North Atlantic and North Pacific.

the general anticyclonic circulation over much of this ocean. The low salinity waters that appear in the northwestern North Pacific are being advected from higher latitudes by the north-to-south flow in that area.

In the western North Atlantic, the main surface flow is toward the northwest south of latitude 20° N. and toward the northeast north of about latitude 30° N. Thus high salinity water is being advected into the northeastern North Atlantic and into the Caribbean area. The low salinity water that exists in the northwestern North Atlantic is the result of advection of low salinity water from higher latitudes by the north-to-south flow in the region.

Conditions along the Equator in both oceans are somewhat more complicated. Except in the easternmost portion of the equatorial North Pacific, figure 5 indicates that high salinity water is being advected into the entire area between the Equator and 10° N. While the computations of salinity are probably not very reliable in this region, the result suggests that high salinity water must be transported across the Equator from the Southern to the Northern Hemisphere. This effect appears to be more important in the North Atlantic than in the North Pacific. This conclusion appears entirely reasonable. According to SVERDRUP (1942), an average of six million m^3/sec. of South Atlantic Upper Water is transported across the Equator from the South to the North Atlantic, mainly along the northeast coast of South America. Because of the relatively long trajectory of this water mass within a region where precipitation is exceedingly low and where evaporation must be high, it has very high salinities. Thus very large positive values should be expected in this region as is shown by figure 5.

A similar situation should exist in the North Pacific, although the transport across the Equator from the South to the North Pacific is probably much less. The relatively low salinities that exist in the extreme southeastern equatorial portion are probably due to the effects of excessive run-off from land surface. The relatively low values in the Yellow Sea are probably also due to the run-off.

According to SVERDRUP (1942, page 125), "In these considerations [WÜST's] the effect of ocean currents on the distribution of salinity has been neglected and the simple relations obtained [between S_0 and $E-P$] indicate that transport by ocean currents is of minor importance as far as average conditions are concerned." This statement might be true when considering only the absolute zonal salinities in the open ocean but, a comparison between figures 4 and 5 leads one to believe that the transport factor is of considerable importance when considering the local values of the surface salinity.

The zonal values for the computed salinities compare well with the zonal values for the observed (summer) salinities which indicates that there is some tendency for the effects of the advection of high salinity water in the western or central portions of both oceans to balance the effects of the advection of low salinity water in the eastern and northwestern portions of the oceans.

If Wüst's formulae correctly describe the results of vertical mixing nd $E-P$ on surface salinities, in the absence of transport across the quator and run-off from land surfaces, the net advective effect in each cean should be zero. However, if he average zonal values for $(S - S_0)$ re plotted on an equal-area scale, s in figure 6, it is found that the ositive areas on the graphs do not xactly equal the negative areas. In he North Atlantic the positive area f the graph greatly exceeds the egative area, indicating that there s a considerable net advection of igh salinity water. This is the exected result, since it has already een shown that a net advection of igh salinity water does take place cross the Equator.

In the North Pacific the positive nd negative areas on the graph are ore nearly equal although there some excess in the negative area dicating a net advection of low linity water. While the differences re probably not important, the xcess low salinity water is probably erived from excessive run-off from nd surfaces. The North Pacific oes not have adjacent seas to conibute high salinity water as do the aribbean and Mediterranean to e North Atlantic. The important ibutary seas which do exist would ainly contribute low salinity water. imilarly, it is known that the fect of advection of high salinity ater across the Equator from the Southern to the Northern Hemisphere much less in the North Pacific than in the North Atlantic. It thus ppears that the absolute salinity values shown in figure 4 are quite liable.

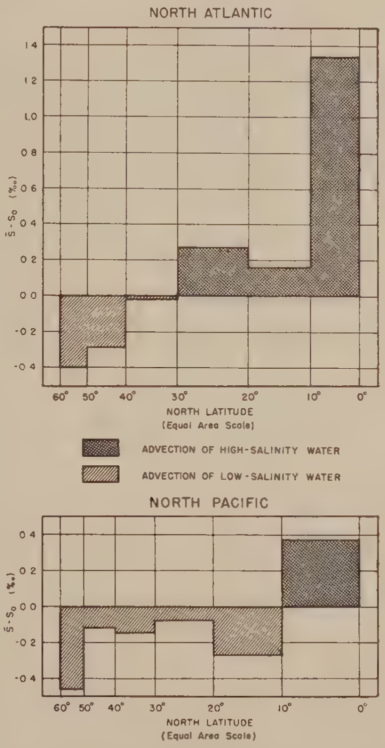

Fig. 6. Difference between the observed summer salinities (S) and the computed annual salinities (S_0) arranged by latitudes on equal area scales.

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PACIFIC SHARPNOSE SHARK *(SCOLIODON LONGURIO)* IN CALIFORNIA AND BAJA CALIFORNIA[1]

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The Pacific sharpnose shark, *Scioliodon longurio* (Jordan and Gilbert), a small species of the family Carcharhinidae, has hitherto been recorded only from the tropical waters of the eastern Pacific, from Panama north to the Gulf of California and to Bahía San Lucas at the tip of Baja California (Beebe and Tee-Van, 1941, pp. 112-113; Fowler, 1944, pp. 184, 204, 379, 477). Recently collected specimens extend the range along the outer coast of Baja California to San Diego County, California. From south to north the new record stations are:

(1) Bahía Santa María, Baja California, at about 24° 45′ N. Lat., 112° 10′ W. Long.: 1 young male, 347 mm. long (extreme total length), collected in a bait net haul by E. W. Kates and Philip Sandoz of the tuna clipper "Renown" on September 3, 1948.

(2) Bahía San Juaníco, Baja California, at about 26° 14′ N. Lat., 112° 27′ W. Long.: 3 young specimens, 343 to 381 mm. long, caught by hook and line in 6 fathoms of water by J. L. McHugh and party on the Scripps Institution of Oceanography research ship "Paolina T," on September 26, 1948.

(3) Bahía Ballenas, Baja California, at about 26° 42′ N. Lat., 113° 32′ W. Long.: 1 half-grown male, 556 mm. long, dip netted by J. L. McHugh on the "Paolina T" on October 1, 1948. It was captured under a light at the surface, where the depth was about 12 fathoms.

(4) San Diego County, California, off Mussel Rock, Torrey Pines Park, at about 32° 54′ N. Lat., 117° 16′ W. Long.: 3 embryos, 309 to 327 mm. long, removed from a female "about 2½ feet long." The adult was caught by hook and line at a depth of 90 feet by Boley Ramsower and Dick Hiner on August 15, 1948.

The capture of all these specimens in a six-weeks period is probably a coincidence, rather than an indication of a northward dispersal, for the outer coast of Baja California has been shamefully neglected by fish collectors. Surface temperatures in 1948 (Hubbs, 1949a, pp. 468-479), as indicated by the records at the Scripps Institution Pier, were presumably not high enough to induce a northward spread.

All these specimens correspond satisfactorily with the most recent and most critical characterization of the genus (Bigelow and Schroeder, 1948, pp. 263-265, 292-293). Their general characters are those of the family Carcharhinidae. Their generic identification is based on the following features: the base of the anal fin is less than twice as long as the base of the second dorsal fin; the spiracle is obsolete; the midpoint of the base of the first dorsal is nearer to the axil of the pectoral fin than to the pelvic insertion; the base of the second dorsal fin is about one-third that of the first dorsal; the longest gill-slit is only about one-fourth as long as the first dorsal base; the teeth are alike in the two jaws; all the cusps are smooth-edged and not swollen at the base and all, except those at the symphysis, are broad-based and oblique, with a notch in the outer edge; the caudal peduncle is smooth-sided and has a prominent subtriangular pit above and below; the anterior margin of the nostril bears a small lobe. The prominent labial furrows near the corner of the mouth will serve to distinguish the species at a glance from any of the other eastern Pacific groundsharks (Carcharhinidae).

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The specific key characters, as given below, do not conform in all respects with those assigned to *S. longurio* by Bigelow and Schroeder (1948, pp. 293-294) and do not fully confirm their distinction of this eastern Pacific species from those of the Atlantic Ocean and the Indo-Pacific area. The origin of the second dorsal fin lies over the posterior part, but definitely in advance of the end, of the anal base; the origin of the first dorsal fin lies directly over the inner tip of the pectoral; the interspace between the tip of the second dorsal and the upper precaudal pit is 1.4 times the horizontal diameter of the eye in the half-grown, 1.3 to 1.6 times in the young and 0.9 to 1.2 times in the advanced embryos; the upper labial furrow in the half-grown specimen is one-sixth longer than the horizontal diameter of the eye, in the young it is only about as long as, and in the advanced embryos about one-fifth shorter than the eye, which, as usual, decreases in relative size with age.

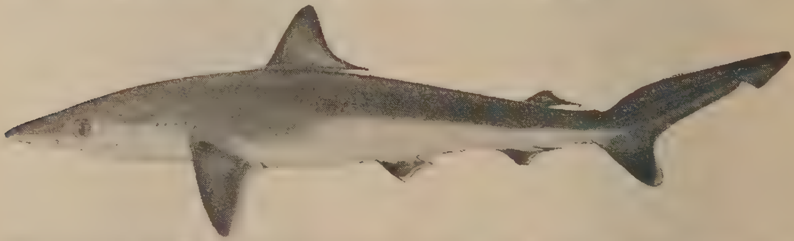

FIGURE 3. *Scoliodon longurio,* half-grown male, *drawn by Mrs. Alma Froderstrom* from a specimen 556 mm. in total length collected in Bahía Ballenas, Baja California.

Whether *Scoliodon longurio* is distinct from the Atlantic species is not certain from the evidence at hand, though it would appear from the accounts by Garman (1913, pp. 109-117), by Meek and Hildebrand (1923, pp. 51-56, pl. 2) and by Bigelow and Schroeder, and from the measurements of our half-grown specimen, that the upper labial fold is longer in the Pacific specimens than in those from the Atlantic. This is the only distinction used in the key by Bigelow and Schroeder. Our specimens do not confirm the supposed differences emphasized by Meek and Hildebrand in the length of the upper caudal lobe, which is about one-fourth the total length, as also in Atlantic specimens as described by Bigelow and Schroeder; or in the relative dimensions of the interorbital and snout, which in our specimens as in those from the Atlantic are subequal. Nor do we confirm the distinctions given by Jordan and Evermann (1896, p. 42), for the upper teeth are not serrulate, nor less oblique than the lowers.

Our specimens have much longer and sharper snouts than do typical examples of the North Atlantic *Scoliodon terrae-novae* (Richardson), but Bigelow and Schroeder unite with *S. terrae-novae* a tropical Atlantic form, *S. lalandii* (Müller and Henle), which has a snout equally as long and as pointed as that of *S. longurio*. They state that the proportions in the two types of the Atlantic intergrade, but, as one of us has pointed out (Hubbs, 1949b, p. 156), there is a gap between the extreme measurements recorded, and it is probable that two species exist in the Atlantic. The fact that a long sharp snout characterizes all known Pacific specimens, including the northern ones here recorded, further suggests that the two types of the Atlantic are distinct species. If so, the problem remains as to whether *S. longurio* is separable from *S. lalandii*, the long-snouted Atlantic form.

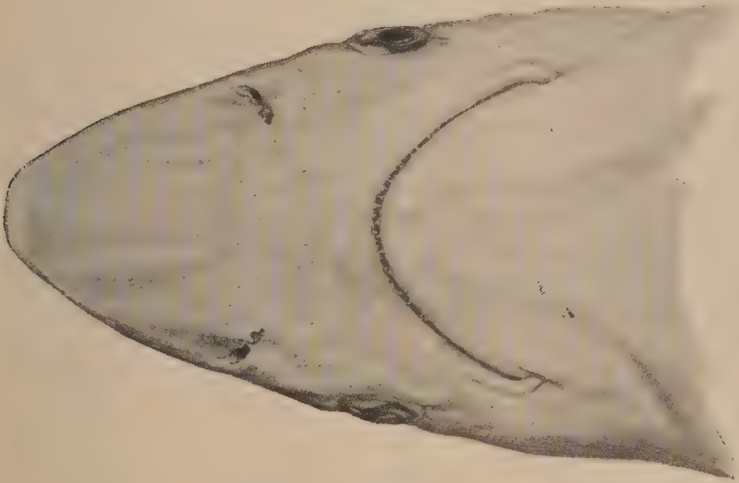

FIGURE 4. *Scoliodon longurio*, lower surface of head of specimen shown in Fig. 3. *Drawn by Mrs. Alma Froderstrom.*

Doubts also remain as to the separation of *S. longurio* of the eastern Pacific from the several nominal species of the Indo-Pacific region. In fact our specimens conform best with the Indo-Pacific *S. intermedius* Garman, as that species is characterized in the key presented by Bigelow and Schroeder. They also run to *S. intermedius* in Fowler's key (1941, p. 132) to the Indo-Pacific species. According to Garman's key, however, *S. intermedius* has a rounded snout. Even if these two forms should prove identical, the identification of our species as *S. longurio* would still hold, by reason of priority. Fowler (1941, pp. 136-137) suggested that *S. intermedius* is probably not distinct from *S. walbeehmii*. A critical study of the whole genus is very much in order. For use in such a study, proportional measurements of our specimens are given in Table 1.

TABLE 1

Measurements of Scoliodon longurio Expressed in Thousandths of the Total Length

Measurements were made by dividers from point to point (not as projections), with parts in normal position. Fins are measured from extreme front.

	Embryos			Young				Half-grown
	San Diego County			Bahía Sta. María	Bahía San Juanico			Bahía Ballenas
Sex	♂	♂	♀	♂	♀	♂	♂	♂
Total length, mm.	310	325	327	347	343	354	381	556
Predorsal length	320	320	326	329	340	326	325	342
Prepectoral length	233	228	243	256	245	249	247	243
Prepelvic length	461	458	471	458	472	457	457	468
Distance between dorsal origins	328	323	324	319	318	316	318	333
Distance between insertions of paired fins	237	237	242	222	232	223	217	239
Pelvic insertion to anal origin	148	145	147	135	134	134	134	146
Origin second dorsal to upper caudal pit	101	100	103	112	99	112	110	101
Tip of second dorsal to pit	26	25	31	40	34	33	33	31
Origin anal to lower pit	116	120	122	130	128	128	134	126
Greatest depth	113	114	111	130	105	114	106	128
Least depth (before pits)	41	41	42	38	34	34	34	38
Greatest width	92	92	96	110	87	86	73	92
Width opposite upper pit	32	31	31	32	22	26	24	29
Distance between front of first and fifth gill-slits	36	38	43	43	42	40	49	49
Length of longest gill-slit	22	24	24	30	22	23	24	25
Head length (to nearest point of first gill-slit)	205	196	205	212	222	218	211	201
Head width (between first gill-slits)	101	95	98	118	109	107	110	113
Interorbital width (fleshy)	94	92	98	97	100	96	97	90
Suborbital width	94	90	93	98	95	93	89	88
Orbit to nostril	29	28	28	30	32	31	30	29
Orbit to junction of lip furrows	38	37	39	46	38	40	36	38
Orbit, horizontal diameter	28	27	28	26	27	26	24	22
Orbit, vertical diameter	30	28	31	29	28	27	26	22
Snout, preocular length	94	95	95	103	108	104	100	101
Snout, preoral length	91	92	92	101	103	99	98	94
Tip of snout to outer end of nostril	61	63	64	69	72	68	66	65
Nostril length	19	18	20	20	20	19	19	18
Internarial width (least)	50	51	52	52	55	53	51	49
Internarial width (greatest)	73	71	76	73	79	75	73	68
Nostril to mouth	35	37	34	38	38	39	37	33
Width of mouth (between ends of gape)	67	68	70	80	72	72	72	76
Front of mouth to line joining ends of gape	48	46	48	40	50	46	48	47
Upper labial furrow	22	22	24	27	23	25	24	25
Lower labial furrow	16	15	18	14	18	17	17	17
First dorsal fin								
Base	93	90	89	95	93	94	104	99
Origin to upper tip	114	110	109	101	109	113	123	104
Lower posterior edge	39	40	39	37	35	37	33	37
Second dorsal fin								
Base	26	28	29	28	29	28	34	31
Origin to upper tip	33	36	35	32	---	37	39	34
Lower posterior edge	47	46	42	43	41	44	45	42
Anal fin								
Base	45	45	43	49	42	47	55	47
Origin to lower tip	44	42	46	46	43	51	50	49
Upper posterior edge	40	42	43	38	38	37	37	37
Caudal fin								
Upper pit to tip upper lobe	258	266	257	264	253	264	259	259
Lower pit to tip lower lobe	102	98	95	98	92	103	102	106
Upper pit to apex of notch in upper lobe	187	197	186	188	184	190	181	186
Upper pit to nearest point of posterior margin	94	93	88	89	87	89	85	85
Lower anterior edge of terminal lobe	34	36	37	37	32	39	36	34
Pectoral fin (depressed downward)								
Base	52	50	55	54	52	57	53	50
Origin to lower tip	117	116	118	118	114	117	122	130
Upper posterior edge	49	46	46	46	41	40	45	47
Pelvic fin								
Base	45	42	41	43	45	46	47	46
Origin to lower tip	50	46	44	48	50	50	50	50
Upper posterior edge	25	26	28	29	26	26	27	27

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Contribution No. 445

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NEARSHORE WATER CIRCULATION RELATED TO BOTTOM TOPOGRAPHY AND WAVE REFRACTION

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(Contribution from the Scripps Institution of Oceanography, New Series, No. 445)

Abstract--The nearshore circulation in the vicinity of Scripps Beach has been measured by means of very simple devices. It has been found that this circulation is controlled to a large degree by the wave convergence and divergence resulting from the diversified submarine relief outside this gently curving shoreline. The position of rip currents is similarly related to the points of wave convergence and divergence. The existence of strong longshore currents flowing against the direction of wave approach is established. The development of large eddies with vertical axes is discussed. Also the pulsating nature of outflowing rip currents is related to alternating groups of high and low breakers.

Introduction

The cyclic changes of beaches have been under observation in Southern California during the past 15 years. The removal of sand from the beaches during periods of large waves and the bring in of sand and rebuilding of beaches during periods of small waves have been clearly demonstrate from these studies [SHEPARD and LAFOND, 1940]. However, the mechanism by which the waves and currents produce this alternate onshore and offshore movement and the nearshore water circu lation associated with wave motion has been poorly understood. Model experiments using dye in tanks [BAGNOLD, 1947] showed that there was a net offshore drift from mid depths to the water surface, and an onshore drift near the bottom. On the other hand, observations by the BEACH EROSION BOARD [1933] near the Long Branch Pier in New Jersey using a floating vertical staff a weighted croquet balls suggested that there was a shoreward movement of water near the surface, and a net seaward drift near the bottom. The observation of rip currents [SHEPARD et al, 1941] has suggested that a considerable amount of circulation takes place around vertical axes.

As one step in the investigation of the exact nature of these water movements a series of sim tests has been made in the vicinity of Scripps Institution. These tests appear to give good evidenc of the general nature of nearshore circulation in an area where there is wave refraction resulting from bottom irregularities. The same general pattern has also been observed in another area of similar bottom topography.

The tests included observations in the surf zone using dye for surface movements and a weigh ball for movements along the bottom. Outside the breakers, observations were obtained by the us of surface floats and by triplanes attached to marker buoys and suspended at various depths. Observations of the currents have been correlated with breaker heights, wave periods, and changes o water level along the shore.

Description of the area

The observations were made off Scripps Beach, which lies just north of La Jolla Point. The coast here is relatively straight, and a sand beach extends for a mile, terminating to the south at t La Jolla Beach and Tennis Club and to the north at Scripps Institution (see Fig. 1). The straightne of the coast is in great contrast to the adjacent submarine topography. On the sea floor two submarine canyons come in to about 700 ft from the low tide shoreline and extend diagonally out from the coast and join a mile from shore. In between the canyon heads there is a gently sloping shelf with an average seaward inclination of 1.3° out to the canyon rims (see Fig. 2 and 3). This shelf i sand-covered in contrast to the canyons where rock and alluvial cliffs are exposed and where the floors are covered with a mixture of sand and silt. Examination of the details of the shoreline (see Fig. 1) shows that there are rocky points south of each of the canyon heads. Less conspicuous sand points are present on either side of the heads of La Jolla and Scripps Canyons. A slight submarine continuation of the sand points is shown by the soundings and is also clearly indicated by th wave-convergence pattern. Almost half way between the two canyons the beach has a concavity

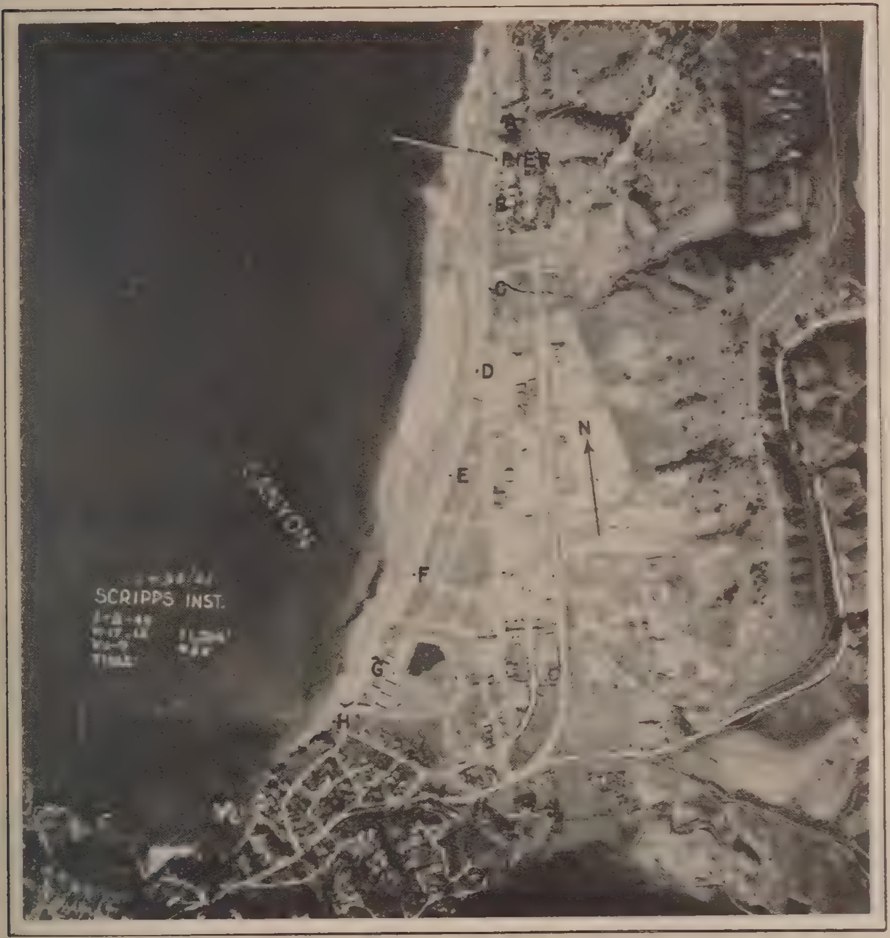

Fig. 1--Scripps Beach at La Jolla, California; note the narrow surf zone at the canyon head, F to G; the wide surf zone at the wave convergence, C to E; and the rip currents on both sides of the convergence at B and E

ich is particularly impressive after the storm season.

The advance of wave crests towards the shore in the area develops a pattern in rough con-
mity with the submarine topography [MUNK and TRAYLOR, 1947]. A refraction diagram for
ves of 14-sec. period approaching Scripps Beach from the west-northwest is shown in Figure 2.
e wave crests near the outer breaker line are convex to the shoreline at the canyon heads and
ncave between them. The effect of this shoreward bend, or divergence, at the canyon head is to
ssipate the energy of the waves and to produce very low breakers. Between the canyon heads the
ves converge, causing a concentration of the wave energy. During long period waves the breaker
ghts at the convergence are several times higher than those at the canyon heads.

Methods and devices

The current-measuring devices used for these preliminary studies of the circulation were all
extremely simple construction. Triplanes (current crosses) were built for measurements out-
le the breakers. These consist of two tin plates 16 inches square which were crossed at right
gles and strengthened by wooden crosspieces. The triplanes were suspended by cod line from
rface floats. The latter are small and float high in the water so that the large surface of the

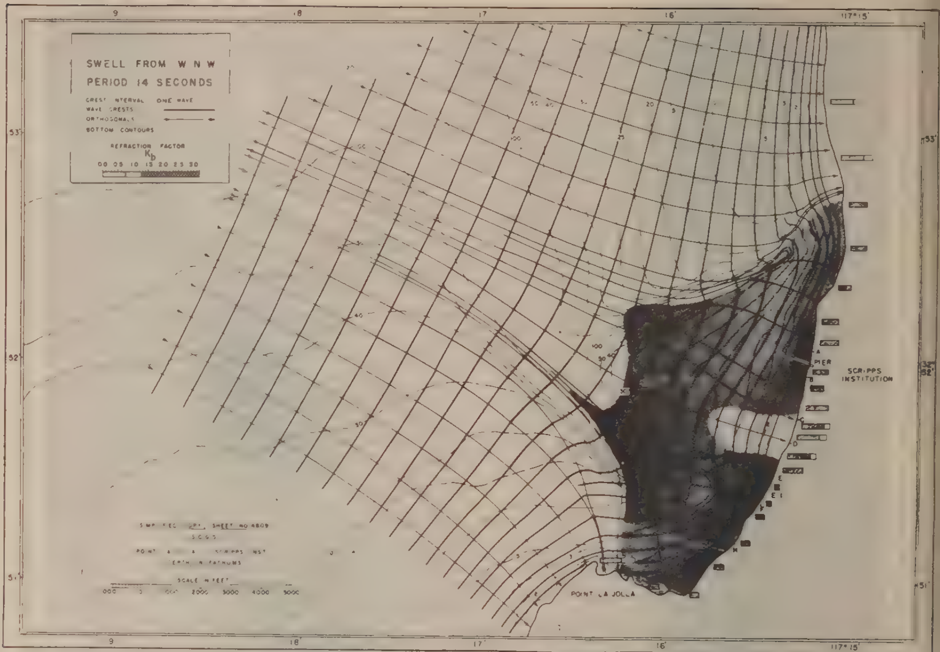

Fig. 2--Refraction diagram for 14-sec waves from the west-northwest; the shaded regions indicate zones of divergence; the lengths of the rectangles opposite the shore stations are proportional to the refraction factor, and thus indicate the variation of breaker heights along the beach [from MUNK and TRAYLOR, 1947]

triplane is much more affected by currents than is the surface float. The depth at which the current is measured is determined by the length of cod line below the float. If there were high wind the surface float would be considerably influenced by them, but no operations were made under th conditions. Also if there were no appreciable currents at the triplane depth the surface float wou control the movement while the triplane would act as a sea anchor. This condition would produce movement in the same direction as the surface float but at only a small fraction of the speed. Si this condition has not yet been observed, it will be assumed that the triplanes were the controllin factor in the observations.

In general, triplanes were set out near the bottom and at mid depths, while surface currents were measured by observations on a drift bottle. The three devices were placed out in close proximity, and the position was obtained by horizontal sextant angles, which give an accuracy to within a few feet because of the nearby, accurately located stations. After a few minutes of drift the boat was nosed alternately up to one float after another, and the time and position obtained at each contact. When the floats were moving toward shore, care had to be taken to pick them up before the triplanes hit bottom. Upon getting into shallow water the triplanes ground during the per of outflow in wave troughs and float free during the inflow accompanying crests, the result favori shoreward movement. During the operation soundings were obtained with a lead line at each obs vation point so far as was possible.

For operations in the surf zone several systems were used. The most practical combined observing the surface current with sea-marker dye and measuring the bottom flow with a weighted ball. A nine-inch volley ball was used, filled with water and just enough mercury to make it slight heavier than sea water. Two observers took a position just inside the breaking waves, while a thi observer remained on shore to time and record their observations. The starting points for the observations varied in depth from 2.5 to 3.5 ft. During the observations, one offshore observer remained as closely as possible at the point where the ball was released. At the same time that the ball was released, some dye was thrown into the water and a signal was given to the shore observ At the end of a 15- or 30-sec period, at a signal from the shore, the man following the ball picked

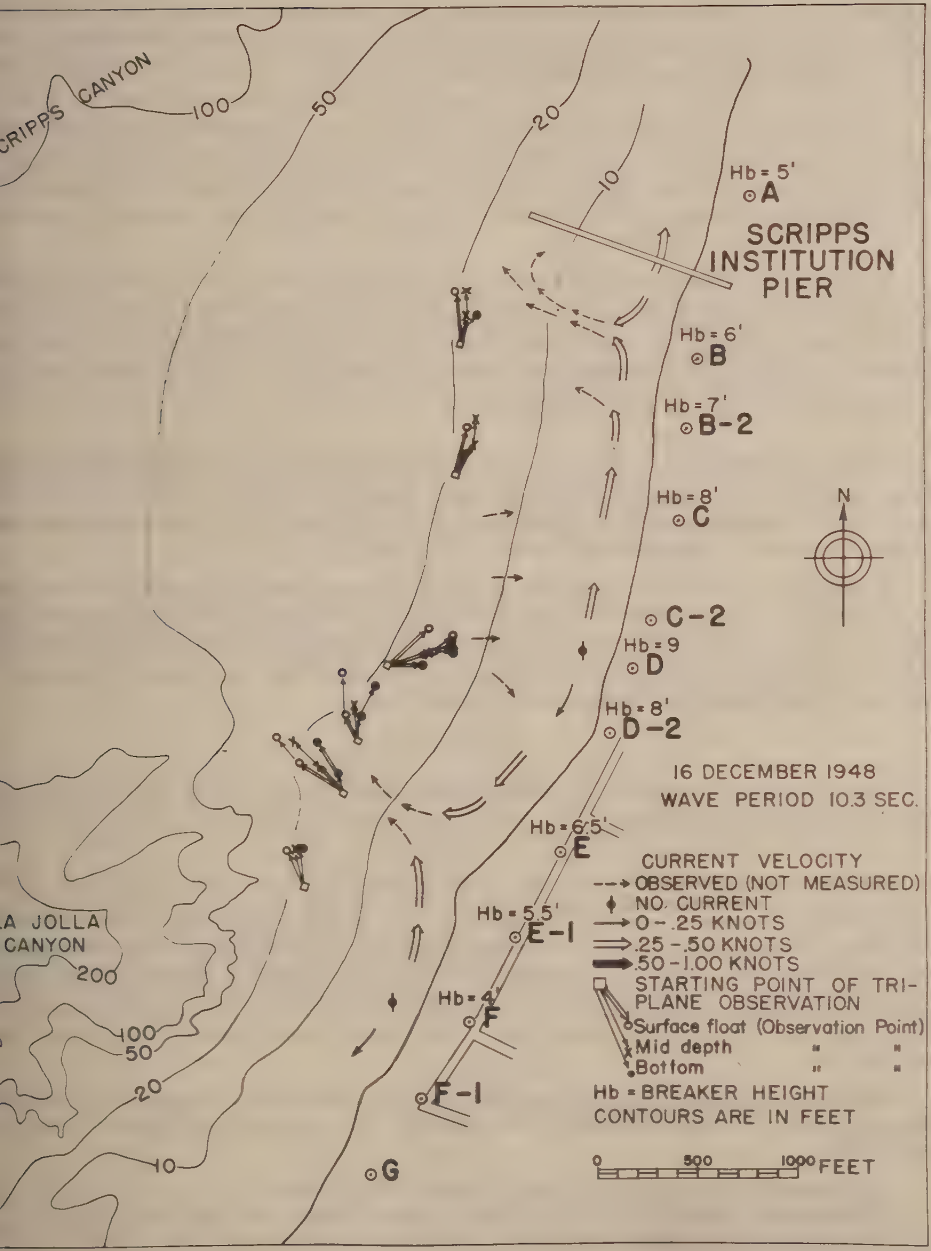
CRIPPS CANYON
100
50
20
10
Hb = 5'
A
SCRIPPS INSTITUTION PIER
Hb = 6'
B
Hb = 7'
B-2
Hb = 8'
C
N
C-2
Hb = 9
D
Hb = 8'
D-2
16 DECEMBER 1948
WAVE PERIOD 10.3 SEC.
Hb = 6.5'
E
CURRENT VELOCITY
OBSERVED (NOT MEASURED)
NO CURRENT
0 - .25 KNOTS
.25 - .50 KNOTS
.50 - 1.00 KNOTS
STARTING POINT OF TRI-PLANE OBSERVATION
Surface float (Observation Point)
Mid depth " "
Bottom " "
Hb = BREAKER HEIGHT
CONTOURS ARE IN FEET
A JOLLA CANYON
200
100
50
20
10
Hb = 5.5'
E-1
Hb = 4'
F
F-1
G
0
500
1000 FEET

Fig. 3--Typical nearshore circulation pattern at Scripps Beach resulting from waves with a period of ten seconds or greater and a northerly flowing coastal current; the longshore and rip currents were measured with the weighted ball, and the currents outside of the breaker zone with surface floats and triplanes; note the diverging currents off stations D and F, and the rip currents off B and E-1 it up. The line attached to the ball, which was marked in fathom lengths, was tightened so that th distance traveled by the ball could be ascertained. One of the observers in the water noted the d tance and the direction of movement of both the ball and the dye. The use of dye instead of a dri bottle for surface currents was found advisable because the drift bottle was almost invariably ca ried shoreward by the surfboard action of the waves.

In conjunction with some of the ball and dye operations, continuous visual observations were made of the breaker heights and of the variation in water level near shore. The latter was obtai by driving a pole calibrated to tenths of a foot into the sand and having an observer call off the a age elevation of the water for each ten or 15-sec period. The breaker heights were obtained by ing the height each breaker rose above mean water level, using the height of eye above mean wat level and the horizon as an index.

Making use of days with no wind, a series of small wooden floats numbered from one to 50 was dropped from a boat at intervals of about 130 ft along a line parallel to the shore. The location of each float was obtained as it was dropped from the moving boat. After dropping the last float, the boat returned to the starting point of the line, and the new position of each float was obtained in succession. This operation was continued until the floats neared the breaker zone or w lost. Later a search was made for the floats on the beach, and on one occasion the time of arriv of a considerable number of them was determined.

All of the above operations were correlated with the wave meters installed at Scripps Institu tion. Wave periods and heights (in addition to the visual observations) were obtained from a Mar III sub-surface pressure recorder [FOLSOM, 1949]. This instrument is mounted on the ocean floor 900 ft off the end of the Scripps Institution Pier in water 40 ft deep. It records surface wav ranging in period from approximately four to over 20 sec.

In addition to the Mark III wave meter, a tsunami recorder [MUNK et al, 1948] was used dur the extended ball and dye observations near Scripps Pier. This latter instrument is mounted on end of the pier and is designed to record low amplitude surface waves with periods ranging from approximately one minute to four hours. The instrument was helpful in that it indicated the presence of waves whose periods coincided with the period between high wave groups as recorded by the Mark III unit and by visual observation of breaker heights.

Terminology

In order to avoid confusion we are suggesting definitions for the various currents associated with nearshore water circulation. Where possible the terms in common use have been retained. However, owing to ambiguity in older usage, we have found it advisable to redefine certain terms

The circulation pattern observed near La Jolla appears to be the result of at least two curre systems: (1) the nearshore system associated with wave motion in and near the breaker zone, and (2) the current system which is more pronounced in the deeper water adjacent to the surf zo The latter, which will be referred to as *coastal currents*, is not related genetically to the waves and the resulting surf. In general, the coastal currents parallel the shoreline and have a relative uniform velocity (as compared with the rapid fluctuations encountered in the nearshore circulatio system). The coastal currents may be composed of one or more of the following; currents (or local eddies) related to the distribution of mass in the oceanic waters, wind-driven currents, and tidal currents.

The nearshore current system is associated directly with the action of waves in and near the breaker zone and with the configuration of the shoreline. The circulation in this system may be s divided into:

(1) Shoreward mass transport of water caused by wave motion.

(2) Longshore currents or movement along the shore, largely confined to the surf zone. The currents are caused by (a) waves approaching the beach at an angle, and (b) the rise in water leve due to the shoreward mass transport by waves.

(3) Seaward return flows compensating for the shoreward mass transport of water by waves
  (a) Rip currents or seaward moving water masses restricted to relatively narrow lanes
  (b) Uniform seaward return flow. There may be processes other than rip currents by which water is returned seaward. MUNK [1949a], in adapting the solitary wave theory to the surf zone, suggests that in addition to rip currents, the shoreward mass transport is compensated by a uniform seaward return flow. This flow would differ from rip currents in that it acts uniformly from the surface to the bottom and is of equal intensity at all points along a straight beach not aff

wave refraction. Superposing this flow on the mass shoreward transport of water due to waves uld result in a net shoreward drift near the water surface and a net seaward drift along the ttom. Model experiments have given varying results regarding the seaward return flow. Tank periments at the Imperial College of Science and Technology [BAGNOLD, 1947] indicated a net award drift from the surface to mid depths and a net shoreward drift along the bottom. Experi-ents by the BEACH EROSION BOARD [1933] suggest a net seaward drift near the bottom and a net oreward drift near the surface.

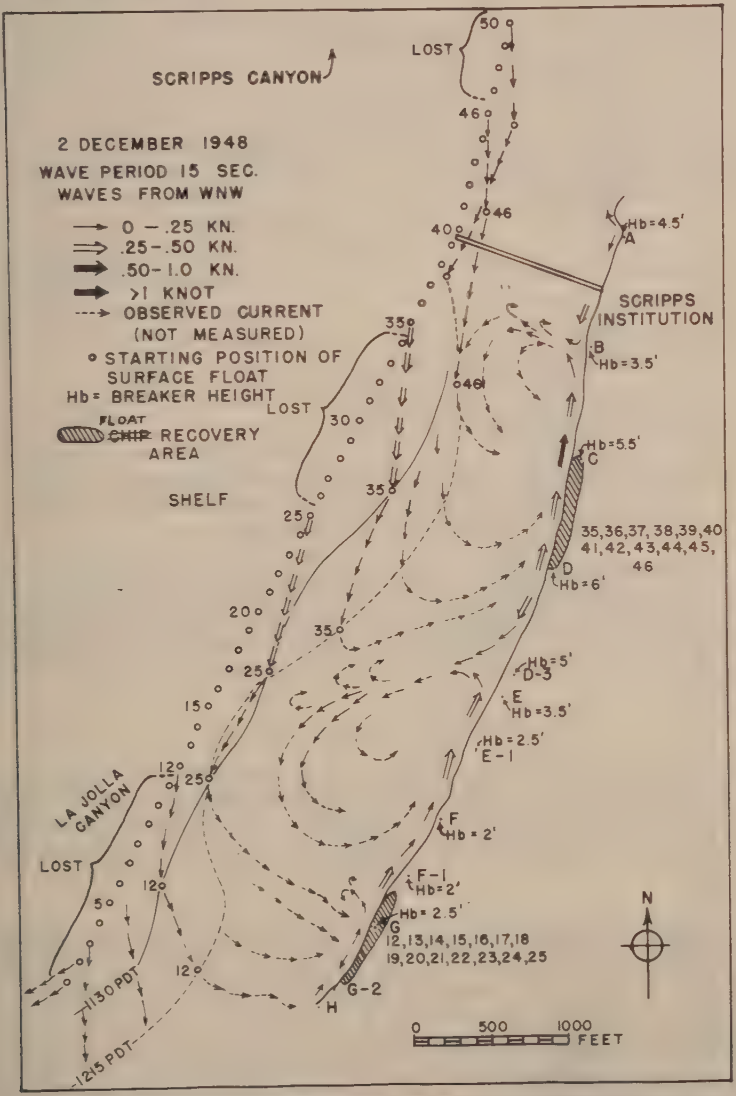
SCRIPPS CANYON
LOST
2 DECEMBER 1948
WAVE PERIOD 15 SEC.
WAVES FROM WNW
→ 0 – .25 KN.
⇒ .25–.50 KN.
➡ .50–1.0 KN.
➡ >1 KNOT
---→ OBSERVED CURRENT (NOT MEASURED)
∘ STARTING POSITION OF SURFACE FLOAT
Hb = BREAKER HEIGHT
▨ FLOAT ~~CHIP~~ RECOVERY AREA
SHELF
LA JOLLA CANYON
LOST
LOST
SCRIPPS INSTITUTION
Hb=4.5'
A
B
Hb=3.5'
Hb=5.5'
C
35,36,37,38,39,40
41,42,43,44,45,
46
D
Hb=6'
Hb=5'
D-3
E
Hb=3.5'
Hb=2.5'
E-1
F
Hb=2'
F-1
Hb=2'
Hb=2.5'
G
12,13,14,15,16,17,18
19,20,21,22,23,24,25
G-2
H
50
46
40
35
30
25
20
15
12
5
46
35
25
12
1130 PDT
1215 PDT
N
0 500 1000 FEET

Fig. 4--Typical nearshore circulation pattern resulting from waves with period greater than ten seconds, and a southerly flowing coastal current; the longshore currents were measured with the weighted ball, and the currents outside of the breaker zone by a series of 50 surface floats dropped along a line parallel to the shore; note that floats 1-11, 26-35, and 47-50 were not recovered; the latter two groups moved seaward during increased rip velocities off stations B and E-1 at 12^h15^m

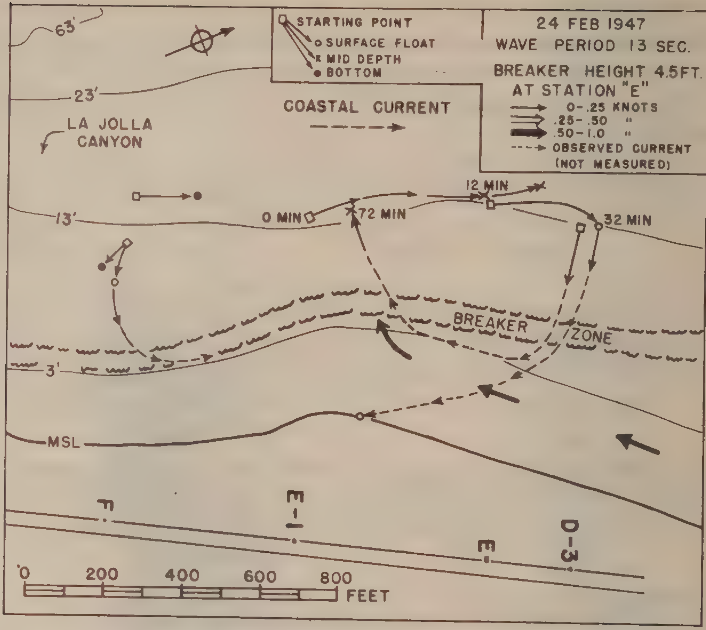

Fig. 5--''Eddy-like'' path of a triplane placed at mid depth off a rip current at station E-1; the triplane completed the circuit in 72 min., having traveled approximately one-third mile

There is no sharp division between areas where the nearshore current system is predomina and those where the coastal currents predominate. With waves of low amplitude and in sections where the beaches are steep it is possible that the effects of the coastal currents may be observe on the beach. On the other hand, under extreme conditions of high waves, the nearshore circulati may completely mask the effects of any existing coastal current out to distances of several thous feet from shore.

General circulation patterns

Combining the various types of measurements of the circulation at Scripps Beach (discussed above) with a considerable amount of observational data gathered over a long period of time, we find that there are several common circulation patterns. The pattern depends on the following factors: (1) the wave period and height; (2) the direction of deep water wave approach; and (3) th direction of the coastal current. The four general patterns which are most typical of this area ar discussed below.

Swell and canyon effect--In the case of a swell having a period exceeding, say, ten seconds, the direction of deep water wave approach does not appear to be an important factor in determinin the general circulation pattern because of the effect of wave refraction over the diversified subma topography [MUNK and TRAYLOR, 1947]. For these longer periods the topography results in grea contrast in breaker height, divergence and very low waves at the canyon heads, and convergences and higher waves over the shelf between the canyons. The point of extreme convergence shifts somewhat up or down the beach depending on the angle of approach of the deep water waves. Figures 3 and 4 show the typical pattern of longshore currents which accompany longer period waves. At the point of convergence the longshore currents are weak and variable. However, away from the wave convergence the longshore currents flow with considerable velocity to the north on the no side and to the south on the south side. It should be noted that these currents flowing away from th zones of wave convergence are actually flowing against the direction of wave approach at the breal line. This forms an important exception to the general rule for straight beaches with parallel con tours, as outlined by PUTNAM, MUNK, and TRAYLOR [1949]. These diverging currents imply tha water is moving shoreward at the wave convergence, and the measurements show that this is indee

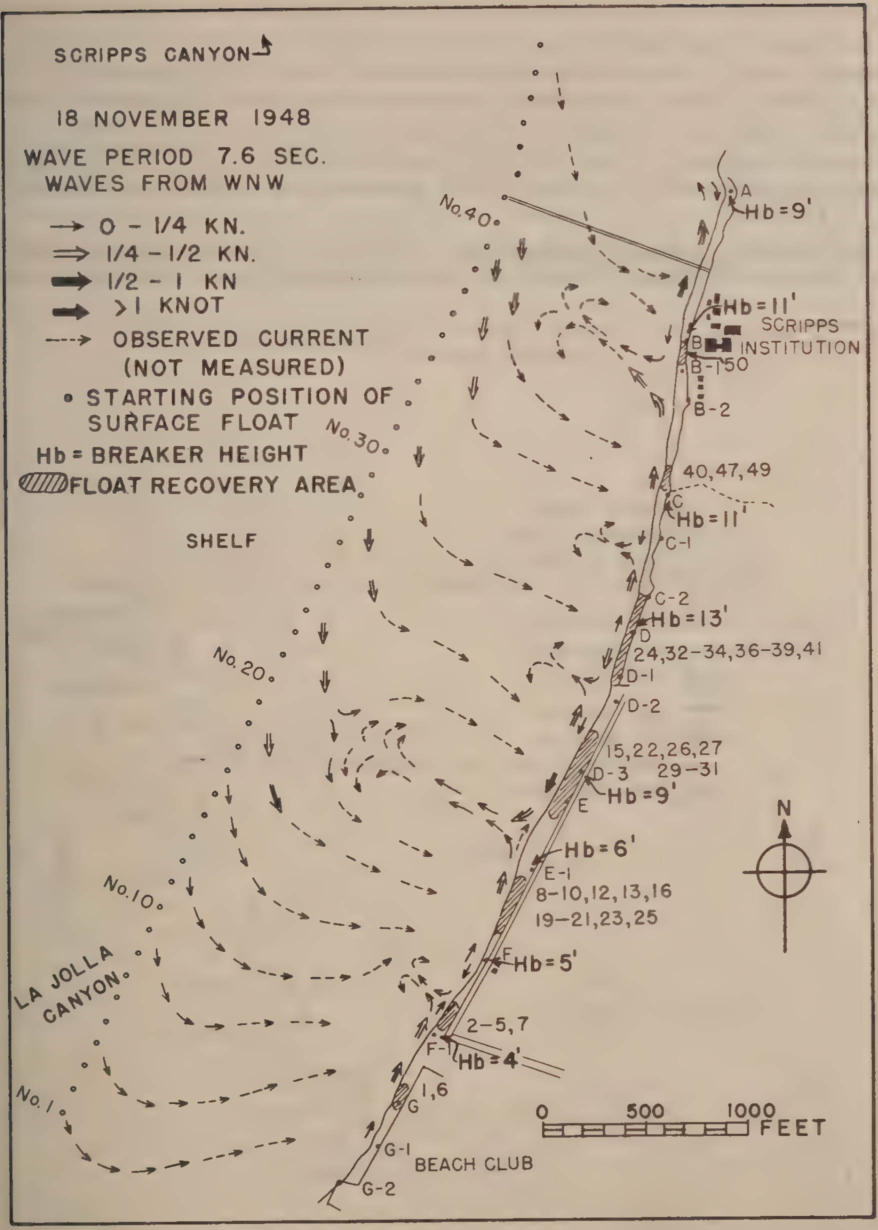
SCRIPPS CANYON
18 NOVEMBER 1948
WAVE PERIOD 7.6 SEC.
WAVES FROM WNW
→ 0 - 1/4 KN.
⇒ 1/4 - 1/2 KN.
➡ 1/2 - 1 KN
➡ >1 KNOT
---→ OBSERVED CURRENT (NOT MEASURED)
• STARTING POSITION OF SURFACE FLOAT
Hb = BREAKER HEIGHT
▨ FLOAT RECOVERY AREA
SHELF
LA JOLLA CANYON
No. 40
No. 30
No. 20
No. 10
No. 1
A
Hb=9'
Hb=11'
SCRIPPS INSTITUTION
B
B-1 50
B-2
40,47,49
C
Hb=11'
C-1
C-2
Hb=13'
D
24,32-34,36-39,41
D-1
D-2
15,22,26,27 29-31
D-3
Hb=9'
E
Hb=6'
E-1
8-10,12,13,16 19-21,23,25
F
Hb=5'
2-5,7
F-1
Hb=4'
1,6
G
G-1
BEACH CLUB
G-2
N
0 500 1000 FEET

Fig. 6--Typical nearshore circulation pattern resulting from waves less than ten-second period approaching normal to Scripps Beach, and a southerly flowing coastal current; note the numerous rip current zones along the beach (compare with Fig. 4); 38 floats were recovered; 11, 14, 17, 18, 28, 35, 42-46 and 48 were lost

e case. At varying distances from the convergence the longshore currents turn seaward as rip
rrents. The rip currents merge into the coastal current outside the breakers. Where these
astal currents are moving toward the convergence, the current makes a complete circuit or an
dy, as in Figure 5 where the complete circuit of a triplane is indicated. Under conditions of

high surf, lifeguards have been swept around in a circuit of this sort while trying to rescue bathe

The currents at the canyon head are somewhat variable, but they show a distinct tendency to diverge as longshore currents flowing away from the canyon head (Fig. 3). These currents, which are a response to the angle of incidence of the waves, also turn seaward into rip currents althoug ordinarily the outflow is very weak, in contrast to the strong outflow from the convergence zone. the north of La Jolla Canyon the outflow joins the outflow south of the convergence. The still wate shoreward of the junction of these two currents results in a condition favorable to deposition. Th condition may produce the projecting point which is so clearly shown on the map at this position (Fig. 3, station E-1).

Short period waves, normal approach--The current patterns accompanying short period wave under nine seconds, differ considerably from those associated with longer period waves, largely

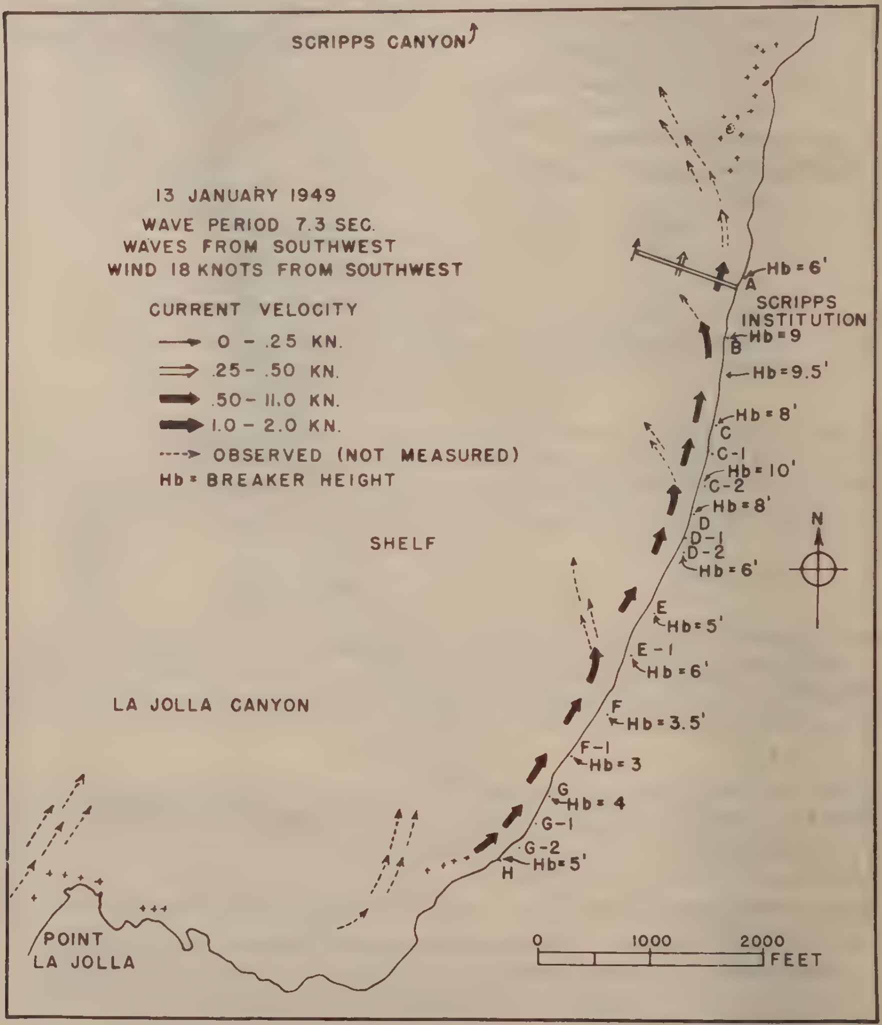
SCRIPPS CANYON
13 JANUARY 1949
WAVE PERIOD 7.3 SEC.
WAVES FROM SOUTHWEST
WIND 18 KNOTS FROM SOUTHWEST
CURRENT VELOCITY
0 - .25 KN.
.25 - .50 KN.
.50 - 11.0 KN.
1.0 - 2.0 KN.
OBSERVED (NOT MEASURED)
Hb = BREAKER HEIGHT
SHELF
LA JOLLA CANYON
POINT LA JOLLA
Hb = 6'
A
SCRIPPS INSTITUTION
Hb = 9
B
Hb = 9.5'
Hb = 8'
C
C-1
Hb = 10'
C-2
Hb = 8'
D
D-1
D-2
Hb = 6'
N
E
Hb = 5'
E-1
Hb = 6'
F
Hb = 3.5'
F-1
Hb = 3
G
Hb = 4
G-1
G-2
H
Hb = 5'
0
1000
2000
FEET

Fig. 7--Typical nearshore circulation pattern resulting from wind and short period storm waves approaching Scripps Beach from the southwest; note that all currents are moving in a northerly direction, including those at the end of Scripps Pier ecause the short period waves produce less wave refraction over the submarine topography. How-ver, where the waves have essentially a normal approach (see Fig. 6), the difference between the irculation patterns accompanying long and short period waves is less striking. The pattern differs rincipally in that the rips are smaller and more numerous, and hence the circulation pattern is omposed of a considerable number of eddy-like cells (compare Fig. 4 and 6).

Short period waves, southerly approach--During local storm conditions in which the waves and vind are from the southwest and when the waves have a short period, the circulation pattern at Scripps Beach is considerably altered (see Fig. 7). Along most of the beach the waves approach he coast diagonally from the south. Judging from the variation of breaker heights, refraction is of some importance, but the angle of wave approach is more pronounced and results in longshore cur-ents to the north along the entire beach. The current weakens somewhat at points south of the con-vergence and south of the divergence, indicating some canyon effect. At several points along the shore there

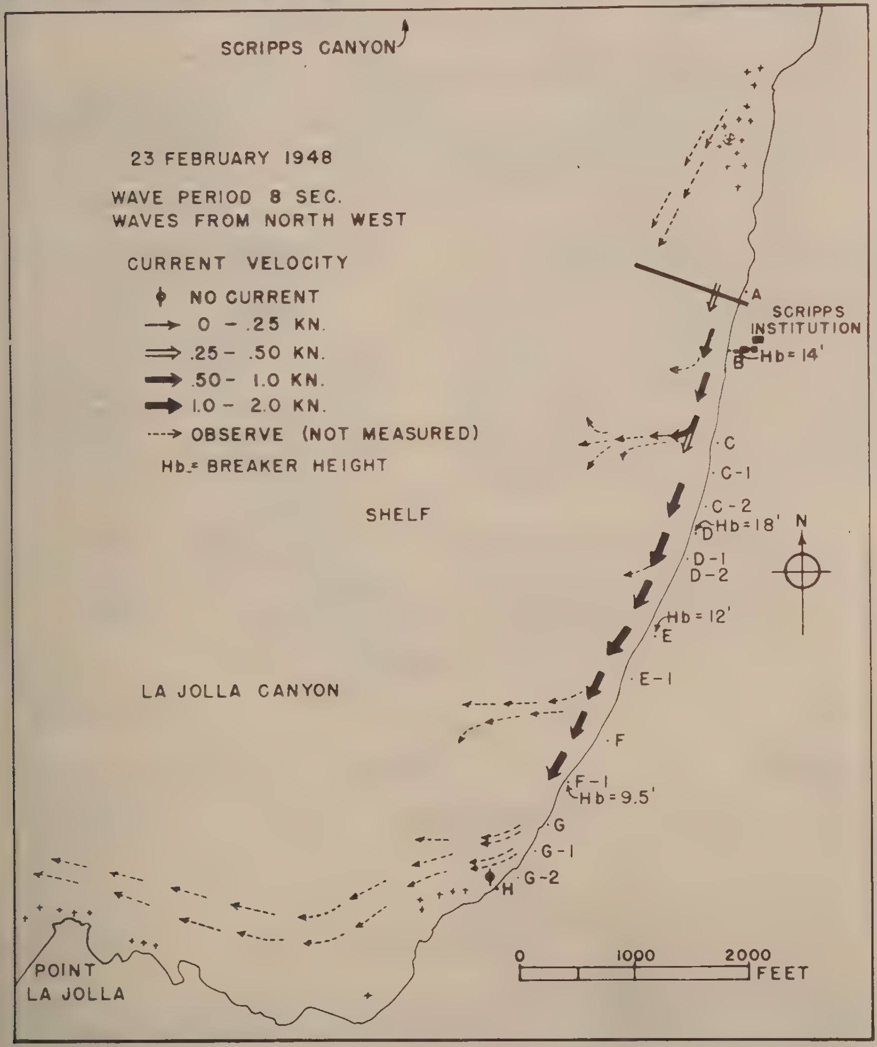
SCRIPPS CANYON
23 FEBRUARY 1948
WAVE PERIOD 8 SEC.
WAVES FROM NORTH WEST
CURRENT VELOCITY
NO CURRENT
0 - .25 KN.
.25 - .50 KN.
.50 - 1.0 KN.
1.0 - 2.0 KN.
OBSERVE (NOT MEASURED)
Hb = BREAKER HEIGHT
SHELF
LA JOLLA CANYON
POINT LA JOLLA
A
SCRIPPS INSTITUTION
B
Hb = 14'
C
C-1
C-2
D
Hb = 18'
N
D-1
D-2
Hb = 12'
E
E-1
F
F-1
Hb = 9.5'
G
G-1
G-2
H
0
1000
2000
FEET

Fig. 8--Typical nearshore circulation pattern resulting from short period storm waves approaching Scripps Beach from the northwest; note that all currents are southerly, with a large outflow past Point La Jolla are rip currents which return some of the excess water that has built up along the shore. The nature of the flow outside the breakers has not been determined except at the pier end where it w found to be to the north.

Short period waves, northerly approach--The most violent storms of the Southern California area accompany northwest winds. During these storms relatively short-period waves build up ra ly and develop spilling breakers in water as deep as 20 to 25 ft. These waves result in a pronoun southerly longshore current along the entire length of the beach (see Fig. 8). As in the case of th

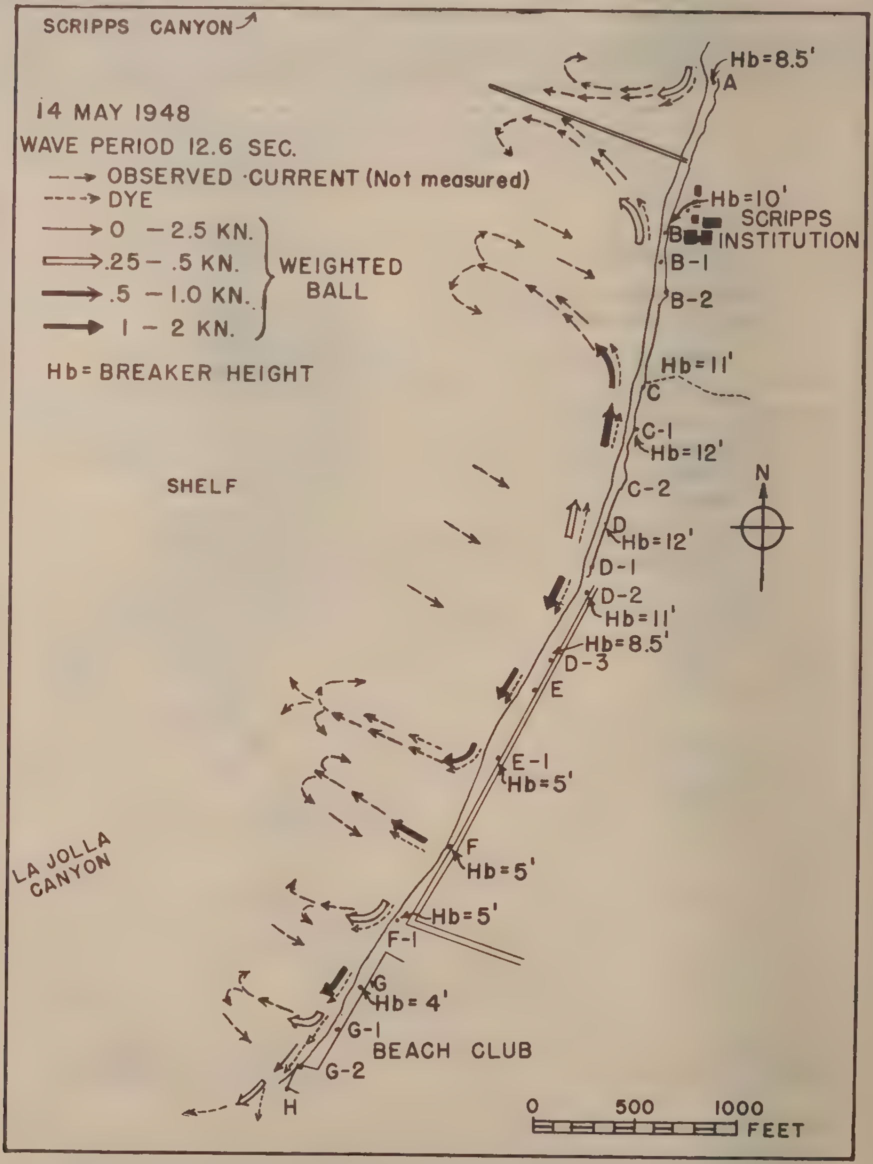
SCRIPPS CANYON
14 MAY 1948
WAVE PERIOD 12.6 SEC.
OBSERVED CURRENT (Not measured)
DYE
0 - 2.5 KN.
.25 - .5 KN.
.5 - 1.0 KN.
1 - 2 KN.
WEIGHTED BALL
Hb = BREAKER HEIGHT
SHELF
LA JOLLA CANYON
Hb=8.5'
A
Hb=10'
SCRIPPS INSTITUTION
B
B-1
B-2
Hb=11'
C
C-1
Hb=12'
C-2
D
Hb=12'
D-1
D-2
Hb=11'
Hb=8.5'
D-3
E
E-1
Hb=5'
F
Hb=5'
Hb=5'
F-1
G
Hb=4'
G-1
BEACH CLUB
G-2
H
N
0
500
1000
FEET

Fig. 9--Nearshore circulation pattern resulting from high waves with a 12.6 sec period hort period waves from the southwest, a pronounced diagonal approach appears to be more impor-ant in determining the longshore current direction than the lateral gradation in breaker height due o wave refraction. The high velocities of the longshore currents associated with these waves, and he fact that their direction is continuous along the entire length of the beach, result in a large mount of sand transport.

The four patterns described above are typical of the various wave periods and directions of eep water wave approach. However, the wave height is also important in determining the circula-ion pattern. Very low or extremely high waves may result in a somewhat different pattern than that escribed for average waves of a given period and direction of approach (compare Fig. 9 with Fig. 3 nd 4). Dependence of the circulation pattern upon wave height probably results from the fact that he volume of water transported shoreward by wave action is proportional to the square of the wave eight [MUNK, 1949a], and that the irregular bottom topography causes a different relationship be-ween the shoreline and breaker line for the cases of waves breaking in shoal and deep water.

Currents as a function of depth

The general circulation has been discussed above without regard to variation with depth. This rocedure was justifiable since the currents from top to bottom had proved to have a similarity of attern. However, there are gradational differences in velocity and direction (Tables 1 and 2). ince the observations do not have complete continuity through the breaker zone, it seems advisable o discuss separately the vertical gradation for the surf zone and for the zones outside the breakers. his is particularly important because different devices were used in the two zones.

Table 1--Variation of current direction with depth in the surf zone

Number of observations		
Surface and bottom in same direction	Surface alongshore, bottom diagonally offshore	Surface onshore, bottom offshore
49	17	1

Table 2--Variation of current direction with depth outside the breakers

Direction of movement	Number of observations		
	Comparison between surface and bottom	Surface and mid depth	Mid depth and bottom
Same quadrant	27	31	27
Different quadrants	5	1	1
Movement in, along,[a] or out together	22	26	19
One along,[a] the other in or out	8	5	7
One in, the other out	2	1	2
Total number of observations	32	32	28

[a] Within 15° of a line parallel to shore

Depth gradation in the surf zone--The variation of currents with depth in the surf zone is not as easily determined as it is in deeper water. Inside the breakers fluctuation in depth due to alternate advance and retreat of waves made the use of triplanes impractical since they were likely to be stranded during the retreat of large waves. Also, drift bottles were not satisfactory since they were carried shoreward by surfboard action of the waves. This action of a floating object does not necessarily indicate the direction or magnitude of the surface current, as was clearly emonstrated by the use of sea-marker dye along with drift bottles. When the powdered dye is rst dropped onto the surface it moves shoreward, but as soon as it is mixed with the water the rection changes according to the circulation pattern; whereas the drift bottle is ordinarily surf-oarded shoreward.

Bottom currents were measured by the weighted ball. Since the ball was slightly heavier an water, it could be expected to show a slight tendency to move downslope under the influence of gravity. However, this effect is probably minor owing to the gentle beach gradient in this area.

Figure 9 shows a number of observations along Scripps Beach in which the direction of surf movement as indicated by the dye, and the bottom movement as indicated by the ball, are compared The center of the diffused dye patch was used as an index of the surface current. During the dye an ball observations the velocity of the ball was determined in all cases, but it was impossible, with th available personnel, to make measurements of the surface currents. However, in the abundant instances when the dye and ball were moving in the same direction, approximate comparisons could be made. It was found that the dye moved faster than the ball in virtually all such cases. An estimate can be ventured that the ball moved at about three-quarters of the velocity of the dye. On the other hand, in some cases where outward movements were observed the ball moved as fast or faste than the dye.

In approximately 73 per cent of the cases the top and bottom currents moved in essentially the same direction. Almost all of the remainder showed diagonally offshore movement at the botto and longshore movement at the surface. Only one case was found where a surface current was moving onshore and a bottom current moving out. The reverse has not yet been observed. The compa sons seem to indicate that the bottom currents move offshore to a greater extent than the surface c rents. This outward differential was found particularly in localities near rip currents. Evidently t bottom water starts the outward movement and the surface currents follow at points near the main outflow of the rip.

Depth gradation in zones outside breakers--Outside the breaker zone measurements were made near the bottom and at mid depth with triplanes and at the surface with drift bottles. The number of comparisons is not large (Table 2), but on all of the days when measurements were made the same tendency was indicated, namely, the majority of the floats moved in the same quadrant at all depths. Comparing top and bottom we found that in 84 per cent of the observations both currents moved in the same quadrant and only 16 per cent moved in different quadrants. Comparing top and middle we found the agreement even larger, 97 per cent agreeing as to quadrant. Mid and bottom currents similarly showed an agreement of quadrant in 97 per cent of the observations.

In the great majority of the observations the currents at all depths agreed in that all three moved shoreward, out, or along shore (within 15° of a line parallel to the shore). Thus in comparin top and bottom we found 69 per cent of the cases were in agreement, 25 per cent had one current moving alongshore and the other moving either in or out, and 6 per cent had shoreward movement o one current and seaward movement of the other. The top and mid depth currents had a closer acco with 81, 16, and three per cent for the same three categories, whereas the mid depth and bottom currents showed 68, 25, and seven per cent respectively.

Many of the triplane observations off areas where rips were operating showed a gradual cha in direction and velocity of the current from the surface to the bottom. This spiral effect is illustrated by the triplane observations shown in Figure 3, and is thought to be the result of the superposition of the seaward flowing rip currents on the coastal current. A breakdown of a typical observation into rip current and coastal current components is shown in Figure 10. Apparently rip currents which have their origin in shoal water near the breaker zone do not extend to the bottom in the deeper water outside the breakers, whereas the coastal current which flows essentially parallel to the contours has a more nearly uniform velocity profile with depth.

At the present stage of the investigation the statistics are not sufficiently numerous to warr conclusions as to the dominance of shoreward or seaward movement of currents at various depths. It is known that these directions vary greatly with time and place. Therefore, an insufficient numbe of observations can produce misleading results.

Rip currents

Rip currents are an integral part of the nearshore circulation system, being especially common in localities exposed to the open ocean. The number of rips along a beach varies widely under different conditions. As explained previously, the location of these zones of seaward moving water is in part a function of the wave period and direction (compare Fig. 4 and 6). With long perio even-crested waves the rip zones are more widely spaced than for shorter-period, more irregular waves. Continued observation of a particular rip indicates that the seaward movement of water is not uniform but pulsating, and temporary complete reversals of current direction are not infrequen

Four sets of observations over a period of five months were made to determine the nature and periodicity of the offshore and onshore currents in areas where rip currents were operating.

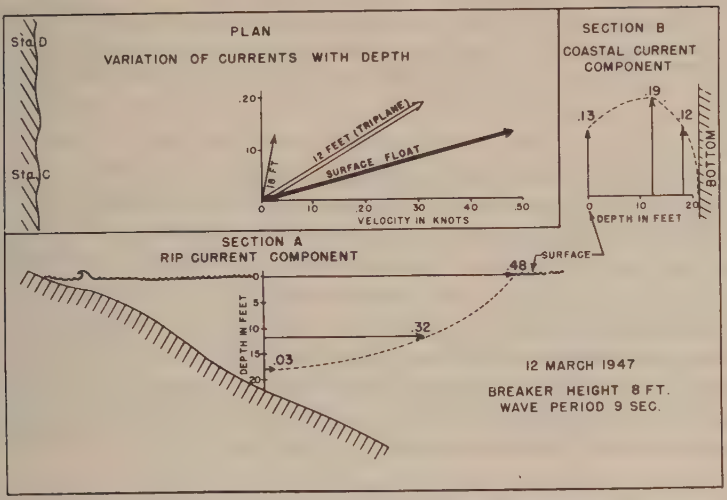
PLAN
VARIATION OF CURRENTS WITH DEPTH
Sta D
Sta C
18 FT
12 FEET (TRIPLANE)
SURFACE FLOAT
.20
.10
0
.10
.20
.30
.40
.50
VELOCITY IN KNOTS
SECTION B
COASTAL CURRENT COMPONENT
.13
.19
.12
BOTTOM
0
10
20
DEPTH IN FEET
SURFACE
SECTION A
RIP CURRENT COMPONENT
DEPTH IN FEET
0
5
10
15
20
.48
.32
.03
12 MARCH 1947
BREAKER HEIGHT 8 FT.
WAVE PERIOD 9 SEC.

Fig. 10--Surface float and triplane observations off station C showing the spiral effect resulting from the combination of a rip current and coastal current

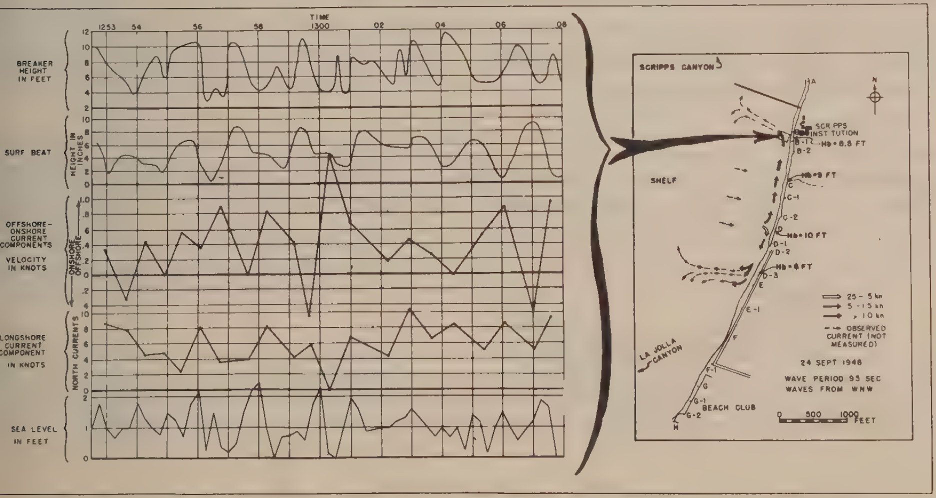

Fig. 11--Extended observations in a rip zone showing the relation between high wave groups, fluctuations in offshore current, sea level changes, and surf beat; the currents were measured with the weighted ball for 15-sec intervals; the observed velocity and direction are the vector sum of the offshore-onshore and the longshore current components; the surf beat was obtained from the tsunami recorder on the end of Scripps Pier

these observations the current directions and velocities were obtained by using the weighted ball. multaneous measurements of breaker height and water level were made. The ball observations ere all conducted in water ranging from 2.5 to 3.5 ft in depth, and about half way between the zone larger breakers and the shoreline. The current observations were broken down into longshore nd offshore-onshore components. These components were then compared with the breaker heights, uctuations in sea level just shoreward of the observation points, and the wave records from the ark III unit and the tsunami recorder.

Ocean waves are characteristically not uniform in height, a group of two or more high waves being followed by a group of small waves. The interval between two sets of high waves may be pe or highly irregular. By introducing a time lag to allow for the wave travel time from the Mark III unit to the breaker zone, a good correlation was obtained between the Mark III record and the observed breaker height. The tsunami record showed waves with periods that coincided with the tim interval between groups of high waves. These oscillations shown by the tsunami recorder appear be caused by the variability of water transported into the surf zone, and are called "surf beat" [MUNK, 1949b]. The relationship of rip currents to (1) wave period and height, (2) the grouping of high waves, (3) surf beat, and (4) the rise in sea level, is illustrated by the observations off Statio B (at Scripps Institution) on September 24, 1948 (see Fig. 11). Measurements with the weighted ball along Scripps Beach showed that there was a rip current off Station B and that the longshore current on the north side of the zone of wave convergence was to the north. At Station B the ball movement was observed for 15-sec periods and these were repeated as rapidly as possible. Analysis of the Mark III wave record and of the observed breaker heights showed that the waves had a period of 9.5 sec and a significant wave height (that is, the average of the highest one-third of the waves) of 8.5 ft. The interval between high wave groups was irregular, but the high and low group were easily distinguished on the record. The results of the analysis of this day's records show that each group of high breakers was followed in sequence by (1) a decrease in the offshore current velocity (sometimes a complete reversal to an onshore current was observed), and (2) a rise in sea level near shore. Following this rise in sea level there was a rapid development of an offshore current which built up to a maximum during the group of low waves.

Analysis of the records of the entire observation (one hour) showed that the average period between minor fluctuations in the offshore velocity was 1.7 min, and that this period was equal to the average period of the surf beat obtained from the tsunami recorder. Major fluctuations in the offshore-onshore current were observed on an average of 7.8 min during the observations (Fig. 11 time, $13^{h}00^{m}$ and $13^{h}08^{m}$). These major changes in velocity may be related to the variability of water transported along shore from the wave convergence zone south of Station B, or to a resonan or "beat note" between the high wave groups and the surf zone. Minor fluctuations in the offshore onshore current which coincided in period with the high wave groups, in addition to periodic major fluctuations occurring at greater time intervals, were characteristic features of all the observatio at points where rips were operating.

The pulsating character of rip currents is indicated by the triplane observations on March 12, 1947 (see Fig. 12). On that date a surface float and two triplanes were placed in the water outside the surf zone off Station C, where a rip was known to be operating. The water at this point was 20 ft deep, and the triplanes were placed at depths of nine and 13 ft respectively. During the first ten

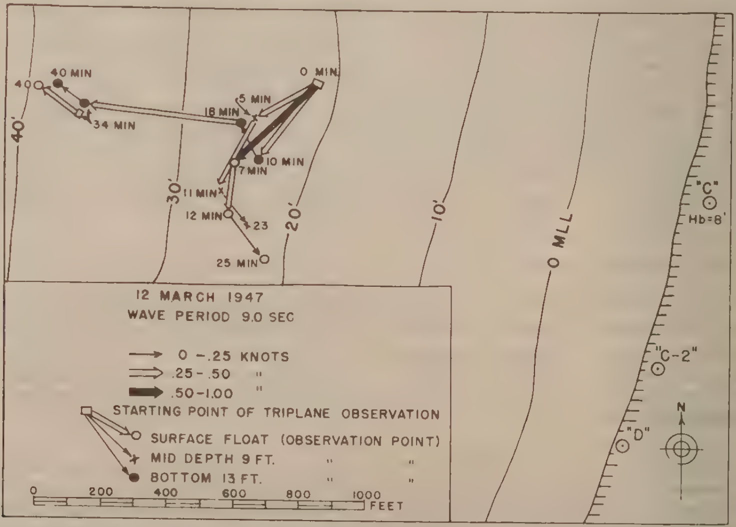

Fig. 12-- Pulsating nature of rip currents indicated by surface float and triplane observations off Station C; the lower depth triplane was caught in a strong offshore current in an area previously traversed in a longshore direction by the surface float and mid depth triplane

inutes of the operation the movement was toward the southwest at all three depths, the surface oat and mid depth triplane leading the lower triplane by 125 ft. Following the tenth minute of the oservation, the lower triplane was caught in a rip current and carried seaward at a velocity of .32 knots through the area previously traversed in a longshore direction by the surface float and id depth triplane.

Conclusions

In areas where diversified submarine topography lies off relatively straight shorelines, the earshore water circulation is ordinarily influenced to a marked degree by the wave divergence the heads of submarine valleys and by the wave convergence over submarine ridges. At the point wave convergence the sea surface is apparently raised a sufficient amount to develop a hydroatic water head and results in diverging currents which flow along the beach in opposite directions vay from the zone of high breakers. These longshore currents flow against the direction of approachg breakers. On the other hand a similar but less powerful outflow takes place along the shore near e point of wave divergence. The latter currents are a response to the direction of wave approach. here the longshore currents from the wave convergences and divergences approach each other, ey turn seaward as rip currents and in some cases join outside the breakers. Between the points outflow there is a zone of quiet water which is favorable to deposition and may account for the nall sand points and sand ridges which protrude on either side of many submarine canyons. Outde the breakers the rip currents are deflected by the coastal currents and move along shore to oints where there is an inflowing current, thus forming a complete eddy or cell of circulation. hese eddies with vertical axes are known to extend essentially from the water surface to near the ottom, the bottom velocities being less pronounced in deeper water (Fig. 10 and 12). There are rdinarily only minor differences in flow directions and velocities in the water column near shore.

The effect of wave convergence and divergence on nearshore circulation is at a maximum during nes of long period waves and is almost as pronounced during times of intermediate period waves th a normal approach to the shoreline. Short period storm waves with diagonal approach definitely terfere with this submarine topographic control of currents and result in longshore currents in e direction in which the waves are approaching. Even in these cases, however, a slight influence the submarine topography can be detected by the variation in velocity of the longshore currents. p currents also accompany the short period diagonally approaching storm waves. These currents e irregularly spaced and are most pronounced at the down current end of the beach.

Long continued measurements of the flow rates accompanying the rip currents have indicated at the outflowing currents are pulsating. Their flow is temporarily checked by a group of large eakers, but the rise in sea level along the shore resulting from these large breakers causes the ow to reach a maximum during periods of small breakers following the large group. Records om the tsunami recorder indicate that the high wave groups are also accompanied by long period ives of small magnitude (surf beat) that have periods similar to the period between high wave oups.

The conclusions from these studies apply only to areas with diversified submarine relief. Hower, since the bottom topography off most coasts is somewhat irregular, it seems likely that these lationships will apply to a limited extent in many areas where submarine contours are essentially rallel to relatively straight shorelines. The latter are known to have wave convergences apparently e to bottom projections of very small magnitude.

Acknowledgments

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COMPARATIVE METABOLISM OF ORGANIC DETRITUS BY INSHORE ANIMALS *

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In any area of biological productivity, the total quantity of unorganized, raw material must considerably exceed the mass of organized living matter. Thus, in different inshore marine areas, we may expect to encounter such numbers and varieties of living animal species as will reflect not only those physical conditions which favor successful harborage, but continuous supplies of raw food materials as well. Rich zones of varied and perennial faunal productivity will be observed in foreshores which are characterized by water of moderate temperatures and freedom from protracted violent impact with the shore. In addition, the presence of gradual slopes, leading up to varied substrates of stationary rocky structures and to sandy beach areas, affords adequate surface for colonization by numerous sedentary forms, and various kinds of refuge for many migratory species. Maximal colonization will be favored by the transport of terrestrial detritus to such areas by rivers, streams or rainfall run-off. Such permanent or seasonal tributaries will contribute valuable raw materials of various kinds, whether in the form of plant nutrient salts or organic detritus commonly associated with humus (Sverdrup, Johnson and Fleming, '42).

This brings us to a brief consideration of the sources, character and disposition of marine detrital organic matter. In the first place, it is derived from the decomposing bodies and dead gametes of countless plants and animals from the largest to the most minute, from the excrement of animals and, at certain regions, from sewage, industrial wastes and other materials of terrestrial origin (ZoBell, '46).

Much discussion has in the past been devoted to the nutritive value of so-called "soluble" organic matter for marine and other aquatic animals. Controversial viewpoints surrounding this question would seem to call for discriminating definition of what is meant by solubility. There is no doubt that many aquatic animals subsist largely upon organic materials which are present in various stages of fine subdivision, including considerable amounts of molecular aggregates of such minute size as to be microscopically invisible. But these entities, if they exceed 1 $m\mu$ in mean diameter or in the longest dimension, are not to be classified as soluble in the true chemical sense, i.e., as molecularly dispersed solutes in the sense which applies to many inorganic salts, amino acids, sugars, etc. Rather, they exist in the colloidal state, sometimes referred to in ordinary parlance as in colloidal "solution," or in that imperfectly defined realm of sizes lying between 1 $m\mu$ and 0.1 μ in mean diameter. Such submicroscopic micelles are visible only in the ultramicroscope, save when coagulated or precipitated into larger aggregates. Dispersed in aqueous media, these biocolloids are readily adsorbed to solid surfaces such as rock, sand or wood, or to hydrophilic substances such as the mucus sheets, cilia and fine sieves which characterize the feeding apparatus of many marine animals.

Marine organic detritus exists in relatively large masses, in coarsely particulate form, and in various grades of colloidal dispersion, with all intergrading sizes represented. Such small quantities of truly soluble organic matter as may be present are in all probability relatively negligible from the standpoint of their direct usefulness to animals, since, in typical cells or body fluids which serve as the source of marine organic materials, some 98% or more of the raw organic substance exists in colloidal or even coarser states, e.g., membranes, fibers, droplets, etc. While marine bacteria which actively decompose masses of organic material certainly hydrolyze protein, lipid and carbohydrate to yield smaller, soluble molecules, these same bacteria are of the sessile or sedentary type, adhering closely to the surface of the material which they are digesting. Prompt and efficient assimilation of the soluble products generated by extracellular digestion of the substrate makes possible the survival and multiplication of the attached bacterial consumers (ZoBell, '46).

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[1] The author gladly acknowledges the help of Messrs. A. S. Lockley and B. H. McConnaughey in obtaining the photographs.

Being chiefly of a hydrophilic character, and carrying negative micellar charges, considerable quantities of colloidal organic detritus are to be found suspended in near-shore waters. The property of "stickiness" or adhesiveness permits their adsorption to submerged marine surfaces such as those mentioned above. Alternatively, large quantities of the material may be precipitated to the bottom by salt-flocculation, by coacervation with other colloids, or by mutual neutralization of electric charges afforded by still other micelles, often of an inorganic nature.

Due to the described conditions which apply to many inshore areas, the magnitude and variety of animal populations are maximal in such regions, and the quantities of organic matter utilizable by them likewise achieve the greatest concentrations in suspended, adsorbed and precipitated form. The value of 5 mg of "dissolved" organic matter per liter of near-shore ocean water, estimated by Krogh and by ZoBell ('46), is doubtless a conservative one, since adsorbed and suspended colloidal material, as well as coarser aggregates, must obviously contribute very substantially to conditions.

It is suggested that some such term as *emulsoid* or *suspended* be substituted for the unsatisfactory word "soluble" as applied to the dispersed organic matter in marine waters. Even were certain aquatic animals to depend upon true organic solutes for a substantial part of their nutrition, the extremely low concentrations of such molecules in surrounding waters would appear to impose the necessity for an enormous output of energy in the form of osmotic work and maintenance, not to mention the complexity and efficiency of the nephritic or other excretory apparatus which would be requisite for handling the vast quantities of water involved.

In addition to readily utilizable compounds such as proteins, certain lipids and hydrolyzable polysaccharides, e.g., starch and glycogen from ruptured cells, numerous relatively inert substances contribute to the organic detritus of the sea. Some of these are cellulose, keratins, chitin, sterols, pigments and the like. The more refractory colloidal members of the complex organic substrate are rendered into cell constituents and molecular by-products by marine bacterial flora of the water and bottom, and are later returned in another form to the general biochemical cycle (fig. 1).

Omitting from the present discussion exclusively carnivorous animals and those others which feed predominantly upon living plant material, we are concerned here chiefly with the numerous species which depend upon the copious supplies of finely divided and suspended, adsorbed or precipitated organic detritus as a primary source of nutrition. While the species of detritus-feeders are many and varied, they have been divided, for the purposes of this discussion, into three main groups, some members of which practise two or more feeding habits as follows:

1. Animals which filter out colloidal and other finely particulate detritus by means of cilia and mucus-covered sieve or net structures. Examples are to be found in the sponges and tunicates, in all or the great majority of lamellibranch mollusks, among the crinoids and among

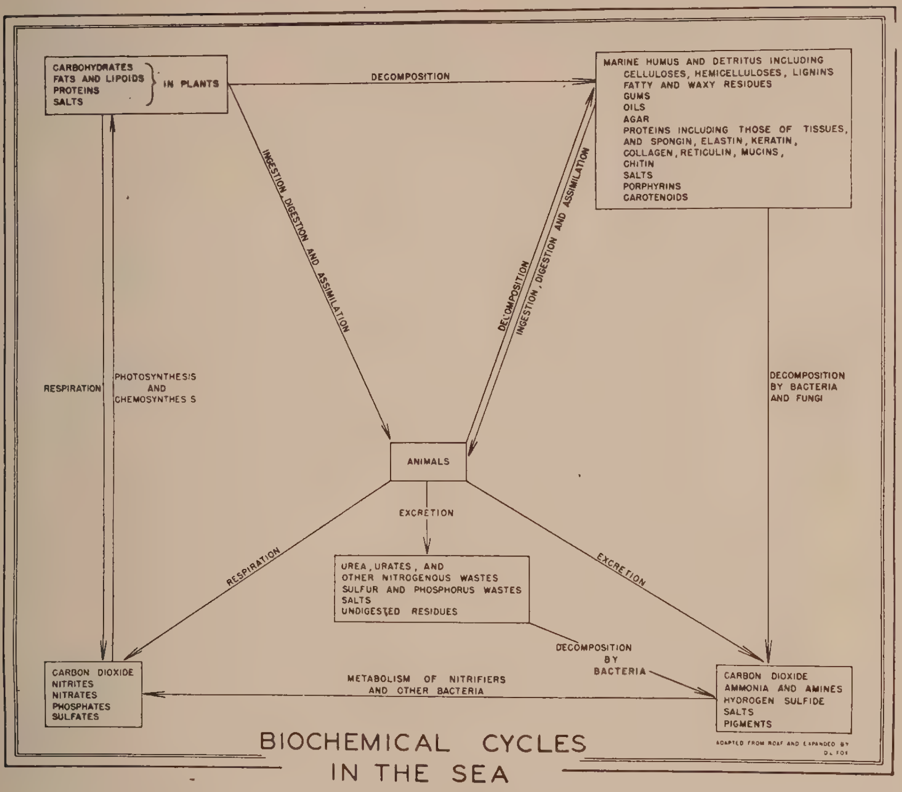
CARBOHYDRATES
FATS AND LIPOIDS
PROTEINS
SALTS
IN PLANTS
DECOMPOSITION
MARINE HUMUS AND DETRITUS INCLUDING
CELLULOSES, HEMICELLULOSES, LIGNINS
FATTY AND WAXY RESIDUES
GUMS
OILS
AGAR
PROTEINS INCLUDING THOSE OF TISSUES, AND SPONGIN, ELASTIN, KERATIN, COLLAGEN, RETICULIN, MUCINS,
CHITIN
SALTS
PORPHYRINS
CAROTENOIDS
INGESTION, DIGESTION AND ASSIMILATION
DECOMPOSITION
INGESTION, DIGESTION AND ASSIMILATION
RESPIRATION
PHOTOSYNTHESIS AND CHEMOSYNTHESIS
DECOMPOSITION BY BACTERIA AND FUNGI
ANIMALS
EXCRETION
RESPIRATION
EXCRETION
UREA, URATES, AND OTHER NITROGENOUS WASTES
SULFUR AND PHOSPHORUS WASTES
SALTS
UNDIGESTED RESIDUES
DECOMPOSITION BY BACTERIA
CARBON DIOXIDE
NITRITES
NITRATES
PHOSPHATES
SULFATES
METABOLISM OF NITRIFIERS AND OTHER BACTERIA
CARBON DIOXIDE
AMMONIA AND AMINES
HYDROGEN SULFIDE
SALTS
PIGMENTS
BIOCHEMICAL CYCLES IN THE SEA
ADAPTED FROM ROAF AND EXPANDED BY D. L. FOX

Fig. 1

sabellid, echiuroid and certain other worms (Coe, '45, '47, '48; Coe and Fox, '42, '44; Fox and Coe, '43; Scheer, '48; Yonge, '36).

2 Animals which graze upon the ocean floor, either (a) utilizing tentacles, arms or similar structures for gathering sapropel (finely precipitated loose organic material on the mud-surface), or (b) sucking in and swallowing whole mud or sand with the use of a muscular pharynx. Among the grazers are ophiuroid, holothurian and crinoid echinoderms and certain crustaceans, while species which swallow whole sand, mud and other included detritus are represented by numerous sipunculid and annelid worms (Yonge, '36; Fox and Scheer, '41).

3. Animals which feed by scraping adherent material from rocks, shells, pilings and other submerged surfaces. Limpets and other gastropods which, with their file-like radulae, typify this habit, swallow organic slime with its included bacteria, sessile algal cells and animal materials (Yonge, '36).

As pointed out by Yonge and confirmed by studies at the Scripps Institution, such animals as bivalved mollusks, which subsist upon finely particulate marine materials, may characteristically possess copious amounts of amylase and glycogenase as extra-cellular secretions in the alimentary tract, e.g., in the so-called "crystalline" style, a long, rod-shaped non-cellular structure extending for the length of a special sac which lies in open communication with the lumen of the gut. On the other hand, such detritus-feeders secrete but insignificant amounts, if any at all, of proteolytic enzymes. Nor are lipoclastic enzymes found free in the gut in appreciable amounts. Protein and fat are therefore digested intracellularly in such species, i.e., following engulfment by special cells of the digestive gland or by wandering phagocytes. Extra-cellular proteases are to be found in copious amounts in carnivorous species such as coelenterates, asteroids and cephalopods, which are incapable of deriving nutrition from plant material.

Although there are similarities in the general nutritive and metabolic habits of detritus feeders, there are also interesting differences in the manner in which certain known molecules are handled by the consumers. Among the many classes of organic molecules associated with suspended matter in the sea, there are some which lend themselves readily to chemical isolation and identification. Such compounds are consequently of value in diagnosing general biological conditions in selected marine localities. The chlorophylls of marine phytoplankton, or these accompanied by greenish degradation products of chlorophylls in muds, in feces, and in water areas of dying plant populations, are frequently measured as approximate indices of plant activities. Similarly, approximate concentrations of the fat-soluble yellow, orange or red carotenoids may be measured instead or in addition. For these lipochromes characterize all green plants, many saprophytes and most animals, the latter deriving the pigments directly or indirectly from plants. Furthermore, the carotenoids generally maintain their molecular integrity for longer periods than do chlorophylls. Thus they may pass through the alimentary tracts of numerous plant- or detritus-eaters without usually undergoing the degradation which chlorophyll does. As a result, carotenoids may often be recovered from detrital materials which yield no chlorophylls as such, and but relatively small quantities of greenish chlorophyll breakdown products (Fox, Updegraff and Novelli, '44).

The subject of marine biochromes has been introduced here because such compounds have proved to be useful in comparative biochemical studies of marine animals, and because investigations of the same pigmentary compounds in marine muds have thrown some light on metabolic chapters of past decades and centuries. The great majority of marine animals investigated to date selectively assimilate and store the xanthophyllic or alcoholic type rather than the carotene or hydrocarbon class of carotenoid. This does not apply to all marine fauna, as will be seen, but seems to be true especially of carnivorous forms, including many fishes, and of numerous herbivores and omnivores, whose tissues may yield solely or chiefly xanthophylls (Fox, '47).

There are, however, some interesting differences among detritus eaters with regard to their carotenoid metabolism. Certain sponges, for example, have been found to exhibit a preponderance of carotenes over xanthophylls, while some of the tunicates assimilate substantial quantities of both types of lipochrome. Numerous lamellibranch mollusks store in their gonads, digestive gland and other tissues only members of the xanthophyll class; this is notably true of the California mussel. The bottom-feeding holothurian, *Stichopus californicus,* yields very small but approximately equal quantities of both carotenes and xanthophylls. Three ophiuroid species studied contained no carotenes at all, but relatively rich supplies of unique esterified xanthophylls. Several bottom-eating echinoid species yield both carotenes and xanthophylls, the former preponderating. The bottom-grazing asteroid *Astropecten californicus* yields many fold the quantities of xanthrophyllic compounds as it contains carotenes (Fox and Scheer, '41). The beach annelid worm *Thoracophelia mucronata,* subsisting on a basic diet similar to that consumed by the other animals cited, assimilates from this mixture only β-carotene, seemingly eliminating α-carotene and largely destroying ingested xanthophylls in the gut (Fox, Crane and McConnaughey, '48).

The foregoing examples are illustrative of the different manner and degree to which various detritus consumers may dispose of ingested carotenoids, and may materially alter the ratio of xanthophylls to carotene members as these occur in the sea. The metabolic habit of assimilating xanthophylls, or of partially destroying them by biological oxidation, and of rejecting carotenes, would appear to be a salient factor in effecting the arresting reversal in ratio of xanthophylls to carotenes observed in muds from the ocean floor. Phytoplankton and suspended material, collectively filtered from sea water by artificial devices or by the efficient mechanism possessed by the mussel, for example, characteristically yield xanthophylls and carotenes in ratios of about 9 : 1. As might be expected, the same general proportions hold for the carotenoids extracted from wave-washed beach sand. But at greater depths in the ocean, the mud surface, yielding lower quantities of total carotenoids, contains greater proportions of carotenes than xanthophylls. At levels beneath the mud surface, from a few inches to several feet, at water depths of 100 fathoms or more for example, carotenes may constitute 80% or more of the total carotenoids. The fact that several bacterial carotenes are encountered in marine mud cores, but that the common crustacean xanthophyll astaxanthin is rarely if ever detected,

TABLE I. *Turnover of water, inert material and organic matter by mussel,* Mytilus californianus
1,000,000 animals from age 1 year to age 2 years

	Age 1 year	Age 2 years	Increment
Total weight	51.2 tons	117.6 tons	66.4 tons
Dry weight tissues	2.3 tons	6.4 tons	4.1 tons
Weight shell	26.0 tons	77.7 tons	51.7 tons
Minimal quantity of water filtered per year (22,000 l. per mussel)			22,000,000 tons
Minimal quantity of organic matter removed from water per year (5 mg. per liter)*			121 tons*
Inert materials filtered from water			ca. 400 tons
Approximate efficiency (*maximal*) $\frac{4.1}{121} \times 100 =$			3.3%**

* Conservative figures; probably too low.
** Probably excessive by 2 or 3-fold.

TABLE II. *Turnover of sand and organic matter by beach worm,* Thoracophelia mucronata
(See plates I and II)

Volume of sand in worm-bed 1 mile long, 10 ft. wide, 1 ft. deep	52,800 cu. ft.
Weight of (dry) sand in this volume	2,820 tons
Total number of worms in worm-bed (ca. 3,000/cu. ft.)	158,000,000
Weight of worms in worm-bed (ca. 0.04 g. each)	7 tons
Weight of sand cycled annually by worms (ca. 84 g. each)	14,600 tons
Ratio of sand cycled annually to sand in worm-bed $\frac{14,600}{2,820} =$ (equivalent to all sand in the bed once every ten weeks)	5.2
Organic matter in sand cycled annually by worms (ca. 1%)	146 tons
Organic matter in worms of the whole colony (ca. 20%)	1.4 tons
Relative efficiency of worms, maintaining a standing population, assuming an annual life-cycle: $\frac{1.4}{146} \times 100 =$	0.96%
Volume of sand on La Jolla Shores beach (wedge 1 mile long, 200 ft. wide, 2.5 ft. high)	1,320,000 cu. ft.
Weight of this sand	70,500 tons
Fraction of sand on beach cycled annually by worms $\frac{14,600}{70,500} \times 100 =$	21%

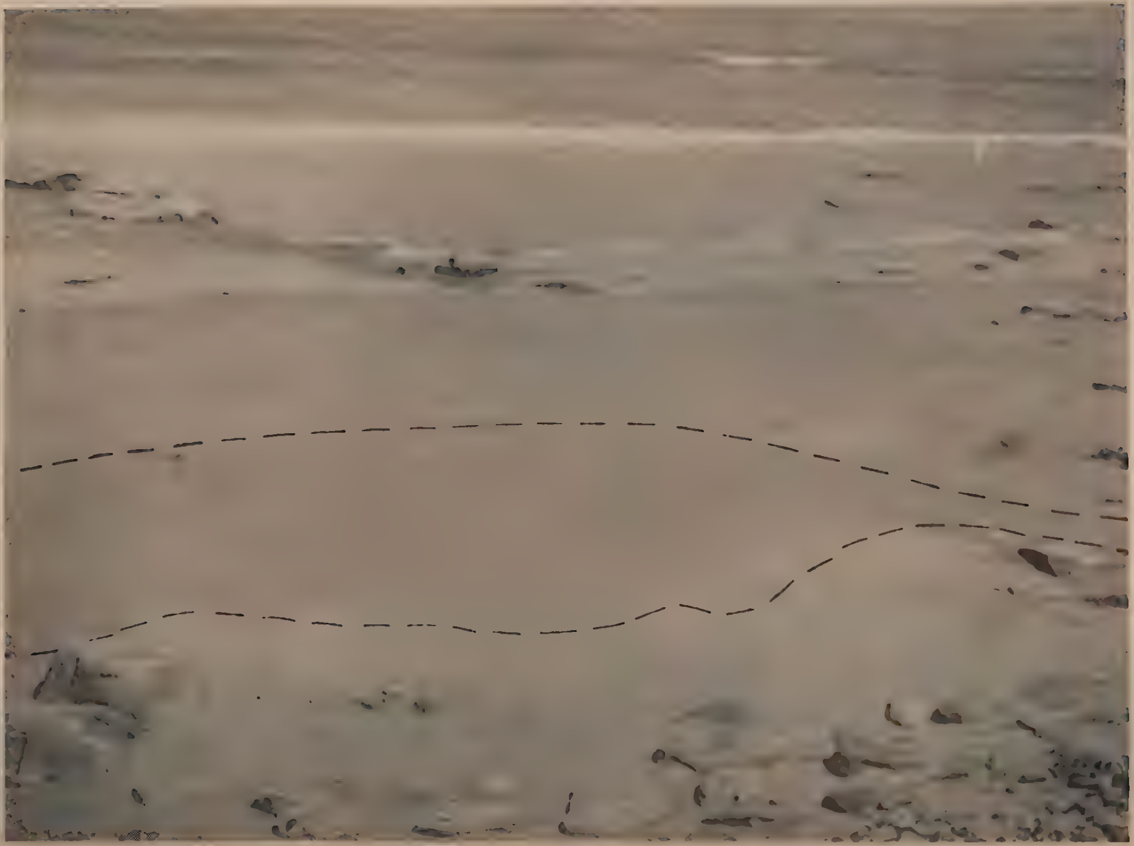

PLATE I. Bed of *Thoracophelia mucronata* (darker area in foreground, outlined) on S. I. O. beach

would lead one to suspect that bacterial flora of the ocean floor may play a role in destroying or chemically reducing xanthophylls.

The right quadrant of the chart (fig. 1) indicates the primary region of discourse in the present contribution. Tables I and II indicate the respective activities of two representative detritus consumers: the mussel, *Mytilus californianus,* each medium-sized specimen of which filters a minimum of 110 grams of organic detri-

No. F661 Students Pocket Rule

Plate II. *Thoracophelia mucronata* (beach worm); close view of colonies on S. I. O. beach.

tus, and several times this quantity of sand, silt and other inert material, from some 22,000 liters of water annually (Fox and Coe, '43); and the beach worm, *Thoracophelia mucronata,* each 40 mg. individual of which cycles annually through its gut a minimum of 84 grams of sand containing about 1% of organic matter (Fox, Crane and McConnaughey, '48).

The photographs (plates I and II) show the beach-excavating activities of the sand-swallowing worm, which occurs in enormous numbers.

It should be emphasized that the mussel does not gain sufficient nutrition from the large numbers of diatoms and dinoflagellates swallowed. These phytoplankton are not present in sufficient numbers to balance the mussel's nutritional budget as determined experimentally by the annual increase of its organic matter (Fox and Coe, '43). Furthermore, dinoflagellates and diatoms, ingested while living, pass through the alimentary tract unchanged in great numbers, and have been successfully cultured from fecal straps removed in an uncontaminated condition from the rectum and placed in nutrient sea water (Coe, '45). The mussel carries no effective cellulase for the digestion of the cellulose envelope possessed by many dinoflagellates (Coe, '45, '47). Nor does the worm *Thoracophelia* subsist upon whole organisms. Its gut contents reveal no recognizable ingested cells, save for a very few minute sessile algae attached firmly to the ingested sand grains. These algal cells appear to be as numerous upon fecal sand voided by the worms as upon the sand before ingestion.

These detritus-consuming animals and their countless allies of similar nutritional habit, at work in inshore regions, especially near river-mouths or other localities of copious run-off, must undoubtedly alter the physical and chemical nature of both the water and the bottom, not only at the site of operations, but also at considerable distances out from shore.

SUMMARY

1. The sizes of populations which will be supported in a marine inshore area are dependent upon the quantities of organic detritus which may serve as food, either directly or by contributing to the total carbon budget.

2. Great numbers of marine invertebrates feed primarily upon organic detritus. They obtain it by (1) filtering such colloidal or other finely particulate material from the water, (2) swallowing whole mud, sand and other inert material to which the organic matter is adsorbed, or (3) scraping it from extensive immersed surfaces.

3. Biochromes, such as red, orange or yellow carotenoids or greenish breakdown products of chlorophyll, provide valuable means of studying the comparative biochemistry of nutrition and assimilation, especially as derived from suspended or precipitated detrital materials.

4. While xanthophyllic carotenoids preponderate greatly over carotenes in fresh, suspended plankton and detritus and in numerous detritus eaters, carotenes are the predominating carotenoids of buried marine muds, and of a few detritophagous animals.

5. Comparisons are drawn between two typical marine detritus feeders: (a) mussels, which filter vast quantities of water annually, removing therefrom the finally suspended organic matter from which some of the xanthophylls are assimilated and the carotenes quantitatively rejected, and (b) the beach-annelid, *Thoracophelia,* colonies of which cycle tons of sand annually through the alimentary tract, gaining nutrition from the adsorbed film of colloidal organic matter, from which β-carotene is selectively assimilated, while xanthophylls are rejected and largely destroyed.

6. Such biological agents and their countless allies alter the chemical and physical nature of both water and floor, not only near the coast but at considerable distances out from shore.

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Contribution No. 447

Reprinted from PACIFIC SCIENCE, *vol. IV, no. 1, January, 1950*

On the Supposed Occurrence in New Zealand of the North Pacific Fish Genus *Sebastodes*[1]

ile attending the Seventh Pacific Science ess in New Zealand I presented a on what I proposed to call the "anti- l" elements in the marine faunas, using neralized term to include what I have ne time been calling "pantemperate" l as what has long passed under the misleading term "bipolar." Many pat- of antitropical ranges were indicated. terest was consequently excited when, afterward, I encountered two speci- n the Dominion Museum at Welling- at were labelled *Sebastodes maccullochi* ps. If the genus *Sebastodes* should be to occur also in New Zealand, we have another example of antitropical- a rather unique type. This large genus, for one species or species group that from Peru to South Africa, is strictly ed to the two sides of the North Pacific. examination of the somewhat compli- evidence indicates, however, that we t have a new case of antitropical dis- on. The specimens that I examined are ble to a well-known New Zealand spe- hat cannot be included in *Sebastodes.* o they represent the species that was bed as *Sebastodes maccullochi* by Phil- (*New Zeal. Inst., Trans. and Proc.* 58: 28, pl. 3, fig. 2, 1927). Nor is that al species properly referred to *Sebas-* The type description and figure call s reference to the genus *Helicolenus.* ugh that genus is essentially pantem- , a new example of antitropical distri- is not provided since *Helicolenus per-* (Richardson) has long been recog- as a member of the faunas of New nd and Australia.

characters evident in the description gure of "*Sebastodes maccullochi*" agree with *Helicolenus* as currently defined, for instance by Barnhart and Hubbs (*Calif. Univ. Scripps Inst. Oceanography, Bul.* 5: 373–377, 385, 1946). There are only 12 dorsal spines (13, rarely 14, in *Sebastodes*) and 5 anal soft-rays (typically 6 to 9 in *Sebastodes*). The dorsal fin begins well backward on the nape, far behind the eye, and is not very deeply notched between the spinous and soft-rayed parts. The spines are not markedly elongated. The pectoral fin has a relatively narrow base, for the lower rays are not procurrent. Some of the upper pectoral rays are branched (not simple as in *Pontinus*). The body is completely scaled and the head is largely scaled. The lateral line is complete In the absence of contrary evidence it can be assumed that the palatines are toothed. The head is relatively smooth, without deep caverns and high ridges, and with only moderately developed spines. The suborbital keel, developed anteriorly, is spineless. The border of the orbit is smooth.

Though a final identification should await thorough comparisons of specimens, it may be suggested that *Sebastodes maccullochi* Phillipps is probably a synonym of *Helicolenus percoides* (Richardson), the only species of *Helicolenus* now recognized from New Zealand. The type figure, from a photograph, certainly resembles very closely the drawing of *H. percoides* published by Waite (*South Austral. Mus., Rec.* 2: 162, fig. 266, 1921). Synonymies of that species have been given by Waite and by Phillipps (*New Zeal. Mar. Dept. Fish Bull.* 1: 53, 1927).

I wish to thank Mr. W. J. Phillipps of the Dominion Museum in Wellington for assistance and numerous courtesies.—*Carl L. Hubbs, Scripps Institution of Oceanography (University of California), La Jolla, California.*

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[1] ntributions from the Scripps Institution of ography, New Series No. 447.

Contribution No. 448

Reprinted from SCIENCE, January 27, 1950, Vol. 111, No. 2874, pages 91–94.

on between Band Slicks at the Surface ternal Waves in the Sea[1]

C. Ewing[2]

pps Institution of Oceanography,
California

slicks on the sea surface like those shown in Fig. nmonly seen along the shore when the wind is a eze. Dietz and La Fond (*1*) of the Naval Elec- Laboratory in San Diego, California, have ob- uch slicks in coastal waters of California, Aus- d Samoa, around the Marquesas Islands, and near rctic ice pack. Woodcock and Wyman (*6*) have and photographed similar "bands of light and pearance" in the Gulf of Panama. They attrib- effect to a systematic variation in the pattern waves on the sea surface associated with a cor- ng variation in wind speed, which they explained of roll vortices caused by convection in the air ms of an internal wave in the air caused by wind ar the sea surface. They observed the effect at speeds up to 7.5 m per sec and described the s oriented with their long axes roughly parallel ind.

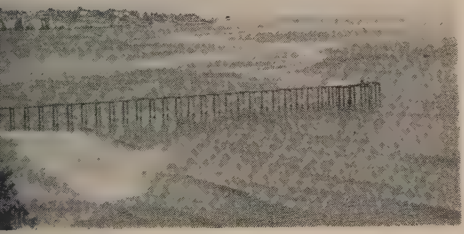

FIG. 1. Typical band slicks.

and La Fond (*1*) have found that the primary sm controlling the formation of slicks in bands of some substance at the sea surface which low- surface tension in the bands where ripples are the role of the wind in this connection being to generate ripples which reveal the peculiar dis- of the surface film. A secondary mechanism sought to explain why the surface film is un- distributed. Detailed observations by the writer vealed that at least two such distributive mecha- re in operation: one, which dominates when the absent or light, is associated with internal waves llow thermocline under the sea surface; the other, dominates at higher wind velocities, is controlled cesses in the air, such as Woodcock and Wyman (*6*) describe. In order to keep the two cases distinct, slicks formed by the first process will in this report be called internal wave slicks, and those formed by the second will be called wind slicks. Internal wave slicks form over the troughs of internal waves, travel with the waves, and are oriented with their long axes parallel to the wave troughs without respect to wind direction. Wind slicks, on the other hand, are independent of internal waves in the sea and are oriented in an approximately downwind direction. The transition from one regime to the other occurs roughly when the wind speed is greater than 3.5 m per sec, i.e., the speed necessary to straighten out light flags and to keep leaves and twigs in constant motion.

More work will be needed to confirm the relationship between band slicks and internal waves, but the evidence so far is convincing enough to warrant a preliminary report. The evidence presented is of two sorts: first, in the series of simultaneous bathythermograph and slick observations shown in Fig. 2, the slicks coincide in every case with depression of the 60° F isotherm and the rippled zones coincide with elevation of the isotherm; and second, when, as in Table 1, the most significant of the observed characteristics of internal wave slicks are arrayed against the oceanic phenomena to which they may readily be attributed, it is seen that short period internal waves give the simplest explanation of the observations, since this phenomenon by itself can account for all the listed characteristics, whereas, of the remaining phenomena in the table, no less than four must be supposed to be operating in concert to account for the complete list.

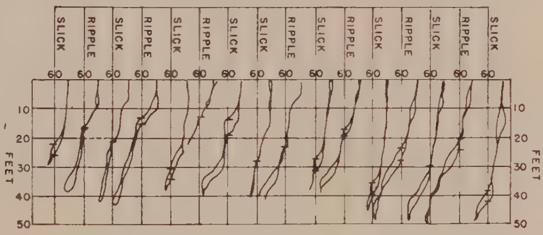

FIG. 2. A series of bathythermograms taken in rapid succession from a moving ship together with simultaneous observations of internal wave slicks, showing the elevations and depressions of the 60° F isotherm in relation to the presence of ripples or slicks at the surface.

Before discussing Table 1 in detail, a brief résumé of the known properties of internal waves will be given, together with a suggested mechanism to account for the uneven disposition of surface-active materials. Fig. 3 is a diagrammatic representation of an internal wave in the thermocline between two layers of water of nearly equal density, where the wavelength is great compared to the thickness of either layer. Internal waves of this type are described by Lamb (*3*), Sverdrup (*4*), Ufford (*5*), Haurwitz (*2*), and others. The fundamental feature causing internal waves to behave differently from ordinary surface waves is the presence over the wave of a fluid nearly as dense as that below. Because of this the potential energy associated with a given deformation is

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author is grateful to the Naval Electronics Labora- n San Diego, for the loan of equipment.

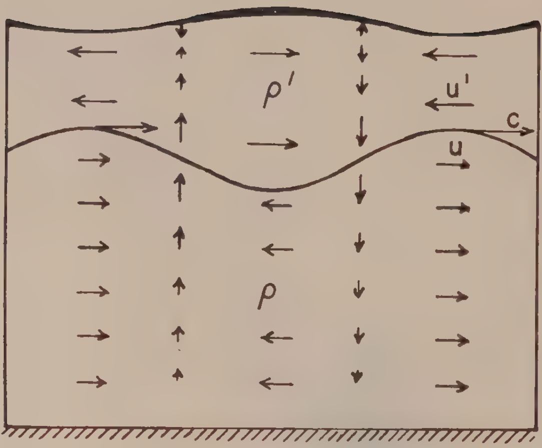

FIG. 3. Schematic diagram of an internal wave in two layers of water of nearly equal densities, ρ' and ρ, where the wavelength is large compared to the thickness of either layer. Shown are the phase velocity, *c*, the horizontal particle velocities in the upper and lower layers, *u'* and *u*, and the associated vertical velocities. The surface layer is alternately thickened and thinned because of the convergence and divergence of *u'*. This effect, as well as the amplitude of the wave at the surface, has been much exaggerated for purposes of illustration. (After Sverdrup.)

TABLE 1

RELATION OF OCEANIC PHENOMENA TO OBSERVED CHARACTERISTICS OF BAND SLICKS

Oceanic phenomenon	Characteristics of band slicks							
	Banding (1)	$c \approx 25$ cm/sec (2)	u' oscillates (3)	$u'_{\max} \rightarrow c$ (4)	$T \approx \frac{1}{2}$ hr (5)	Persistence (6)	Refraction (7)	Independence of wind (8)
Transport by wind or current			X			X		
Transport by surface waves	X*		X		X			
Internal waves in the air							X	X
Roll vortices in the air							X	X
Surface waves, swell, seiche		X		X				
Tides, as waves	X	X			X	X		
Internal waves in water	G†	G	G	G	G	G	G	G

* X = bad fit.
† G = good fit.

much reduced, while the inertia of the system as a whole is increased. Consequently, when an internal wave is compared to an ordinary surface wave of similar length, it is found that the speed of propagation, or phase velocity, of the internal wave is diminished in the ratio $\{(1-s)/(1+s)\}^{1/2}$, where s is the ratio of the density of the upper to that of the lower fluid. For the usual case in the sea, this factor is of the order of 10^{-2}. The orbital motion of individual water particles for the case diagrammed in Fig. 3 is in opposite sense in the two layers. In the upper layer, the orbits are ellipses whose horizontal axes are uniform throughout the layer and
vertical axes vary inversely with the distance abo
thermocline. Thus the horizontal component of p
motion is the same at all depths in the upper layer,
in the direction of wave propagation over the trou
the wave and in the opposite direction over the

The vertical component of particle motion, on the
hand, is comparable to the horizontal component o
the thermocline, decreasing rapidly above this lev
vanishing at a depth of a centimeter or so belo
free surface. At still higher levels the vertical mo
reversed, so that, at the free surface, there exists a
of very low amplitude exactly out of phase wi
wave at the thermocline. It can be seen in Fig.
the horizontal particle velocities are convergent wh
the thermocline is descending and divergent where
thermocline is rising. The convergence is most i
halfway between crest and trough, but its cum
effect is greatest over the trough of the lower
Thus, if the water above the thermocline were im
divided into a number of layers, each layer wo
thickest over the trough of the wave and thinnes
the crest. This effect, acting on a surface film
tially uniform thickness, would distort it into alt
bands of greater thickness over the wave trough a
thickness over the wave crest. Thus a slick wo
formed by temporary thickening of the surface
a given area during the time the trough of an i
wave was passing beneath it. The zone of thick
rather than the material itself, would thus progres
the internal wave. The effect of a wind-driven
on this mechanism would depend on the size of its
slick component. For small values, it would mere
place the slick with reference to the trough. At
values it would cause the slick material to drift w
wave so that the material in a given slick would
the same. At values greater than the critical, the
driven current would completely dominate the sli
terial and would then produce wind slicks nearly
pendent of internal waves, in the manner descri
Woodcock and Wyman (*6*).

The characteristics of wave slicks listed in Table
based on the following observations:

1. *Banding.* The slicks are about 30 m wide an
many kilometers long. They lie in roughly paral
ployment, as bands of clouds sometimes do, separa
zones of ripples about 300 m wide. Ufford (*5*)
internal waves off San Diego of from 100- to
length between crests.

2. *Slick velocity, c ≈ 25 cm/sec.* Time-motion
show that internal wave slicks often move in a di
perpendicular to their long axes at a uniform and
speed of about ½ knot. This velocity is relatively
in deep water. Ufford (*5*) found the phase velo
internal waves to be from 0.07 to 0.68 knots.

3. *Particle velocity, u', oscillates.* Floating
execute oscillatory motion perpendicular to the lo
of a passing slick. They are drawn into the on
slick, held in the slick for a time, and finally expe

nearly resuming their initial position.
ximum horizontal particle velocity, $u'_{\max} \to c$.
while floating in a slick, advance for a time at
significantly comparable to the phase velocity.
gh particle velocities are characteristic of in-
aves.
iod, $T \approx \frac{1}{3}\,hr$. Internal wave slicks usually
st a point at intervals of from 15 to 30 min.
ound internal waves with periods from 9 to 136

sistence. Slicks persist in spite of horizontal
ffusion. This shows that they are continually
ned by a disturbance moving with the slick.
fraction. Internal wave slicks, in water less than
eep, are oriented approximately parallel to the
contours. Thus upon approaching submarine
, for example, they are bowed into the canyons
nanner of long period swell. The speed of in-
aves depends partially on the water depth below
mocline. For the case described above the speed
by:

$$c^2 = g \frac{h h'}{h + h'} \frac{\varrho - \varrho'}{\varrho}$$

where h refers to the thickness of the layers ϱ refers to their densities and the primes refer to the upper layer.

8. *Independence of wind.* In the absence of wind, band slicks are not visible because there are no ripples, but floating objects are often observed to be marshalled in long rows at the sea surface. As soon as the wind arises it is seen that slicks form along these rows. At wind velocities less than about 3.5 m per sec the orientation of the slicks is independent of wind direction.

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Contribution No. 449

A NEW DIATOM FROM SOUTH AFRICA—*CHAETOCEROS PARALLELIS*.*

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Scripps Institution of Oceanography, La Jolla, Cal.

(Communicated by J. H. Day.)

(With one Text-figure.)

(Read November 19, 1947.)

(Latin Summary of the Species available if required.)

Chaetoceros parallelis n. sp.—Cells solitary, rectangular in broad girdle view. Valves concave, elliptical in valve view. Valve mantle fairly high, with slight constriction at junction of valve mantle and girdle zone. Slender setae originate at cell corners and run almost parallel with pervalvar axis, slightly convex on outside. Chromatophores numerous cocciform bodies. Width of cell in girdle view 10·8–13·5 μ, length 21·6–28 μ, length of setae 121–135 μ.

This delicate form occurred in collections made in the neritic province of the west coast of South Africa between Lamberts Bay and Cape Point.

It is tentatively placed in the section Simplicia although its numerous chromatophores may exclude it from this section.

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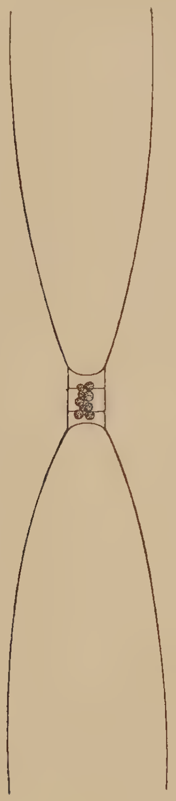
* Contributions from the Scripps Institution of Oceanography, New Series, No. 449.



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SOME MARINE PLANKTON DIATOMS FROM THE WEST COAST OF SOUTH AFRICA.*

By Brian P. Boden, the Scripps Institution of Oceanography of the University of California, La Jolla, Cal., and Zoology Department, University of Cape Town, South Africa.

(Communicated by J. H. Day.)

(With 100 Text-figures.)

(Read November 19, 1947.)

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Preface.

I would like to express thanks to Professor J. Day, Zoology Department, University of Cape Town, for the financial assistance necessary in the preparation of this paper. Thanks are due also to Dr. Marston Sargent, and Dr. Martin W. Johnson, the Scripps Institution of Oceanography, University of California, and to Professor Wesley Coe, Osborn Zoology Laboratory, Yale University, for many valuable suggestions. I am especially indebted to Miss Elizabeth Kampa, the Scripps Institution of Oceanography, University of California, for her painstaking and laborious work in the correction of the manuscript.

Introduction.

The material upon which this report is based was drawn from the collection of the Division of Fisheries for the Union of South Africa for the years 1945–46, the collection of Dr. E. Roux of Vitamin Oil Co. Ltd. for the same period, some samples taken by Mr. J. T. Robinson of the Transvaal Museum, and some samples taken by me in the early part of 1945. All samples were taken in the area extending from a point just north of Lamberts Bay to a point just south of Cape Town. All were taken from the neritic province.

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* Contribution from the Scripps Institution of Oceanography, New Series, No. 451.

An endeavour has been made to list those species which apparently occur most frequently. However, reliable data on this point are lacking, due to the widely differing methods employed in collecting. Doubtless many species have been missed completely.

Numerous expeditions have occupied stations in this area before, but of these the "Valdivia" and "Discovery" are the only two, embodying full-scale diatom reports, which list the diatoms collected at each station. The South-West African species reported by Dr. Karsten of the "Valdivia" Expedition (68, 1905) and Dr. Hendy of the "Discovery" Expedition (62, 1937), but not found in the material reported upon herein, have, nevertheless, been included for the sake of completeness, and reference has been made to the source from which they were drawn. A search has been made through the literature for the clearest and most diagnostic figures of these species, and these have been borrowed freely, and reference made after each figure to the original author.

A general discussion of the structure, biology, and physiology of diatoms has been omitted as being outside the scope of this paper. However, most of the larger reports on diatoms contain discussions of this topic, and of these, Hustedt (1930), Lebour (1930) and Cupp (1943) are particularly good.

The classification followed herein is that of Schütt (1896), with modifications by Hustedt (1930–37). Attention is drawn also to the rather attractive classification propounded by Hendy (1937).

According to Sverdrup *et al.* (115, 1942, pp. 627, 628), in agreement with the dynamics of currents in the Southern Hemisphere, denser water of low temperature is found on the right-hand side of the Benguela current flowing up the west coast of South Africa. Under the influence of the prevailing winds surface layers are carried away from the coast and an upwelling of cold water occurs during most of the year. As a consequence of this upwelling, a band of water of low temperature is found along the coast extending to a distance of about two hundred kilometres, considerably wider than the continental shelf in this area (Shepard, F. P., 109, 1948). The presence of many warmer water forms such as *Fragilaria granulata* and *Stephanopyxis palmeriana* in the neritic province of this region would appear to be inconsistent with this. An examination of the surface currents as indicated by drift bottles, however (45, 1902, p. 155), reveals that temporary currents occur which would be capable of carrying such forms from the warmer east coast. These forms probably appear more as guest-forms than as being typical of the plankton community of this area. On the other hand, these forms may lie dormant in localized regions throughout most of the year and appear periodically in the plankton in noticeable numbers in response to local warming. A much more intensive study of both east and west coast plankton is needed, and much more oceanographic data are required before the endemic plankton communities can be evaluated, and before it can be said with any degree of certainty that a particular species is present as a guest-form or as an endemic form. However, since the hydrographic conditions of the two areas differ so widely, it is highly probable that the east and west coast communities are fairly distinct in spite of very many common forms.

METHODS.

All samples were preserved in formalin and sent to the Scripps Institution for examination. The plankton was washed in distilled water 5 or 6 times, allowed to settle for several hours and the supernatant water drawn off between washings. A hand centrifuge was used occasionally, but this tended to break up the more delicate chains.

Strewn plankton mounts were used throughout the investigation. Preliminary examination was carried out on plain water mounts. Frequently the best results were obtained from air-dried material mounted on a cover glass.

Hyrax, with a refractive index of 1·82, was the mountant used in preparing permanent mounts. The material was placed on a cover glass and either air-dried or very gently warmed. When dry, a drop of Hyrax was placed upon it and allowed to stand until the solvent had evaporated. The cover glass was then reversed and placed on a gently warmed slide. The cover glass could then have been sealed with lacquer or gold-size for more durable mounts.

For a detailed examination of the more robust and strongly silicified organisms the material was cleaned in acid. The plankton was boiled in concentrated hydrochloric acid, and concentrated nitric acid was carefully added to the boiling solution. When oxidation of the organic matter was complete (nitrous acid fumes ceased to be liberated) the frustules were allowed to settle and were well washed with distilled water.

Occasionally it was found desirable to flame some of the heavily silicified frustules to red-heat before mounting.

CLASSIFICATION OF THE CENTRICAE.

BACILLARIOPHYCEAE.

- A. **CENTRICAE** Schütt.
  - I. **Discoideae** Schütt.
    - 1. Coscinodisceae Schütt.
      - *a.* Melosirinae Schütt.
      - *b.* Skeletoneminae Schütt.
      - *c.* Coscinodiscinae Schütt.
    - 2. Actinodisceae Schütt.
      - *a.* Actinoptychinae Schütt.
      - *b.* Asterolamprinae Schütt.
  - II. **Solenoideae** Schütt.
    - 3. Solenieae Schütt.
      - *a.* Lauderiinae Schütt.
      - *b.* Rhizosoleniinae Schütt.
  - III. **Biddulphioideae** Schütt.
    - 4. Chaetocereae Schütt.
    - 5. Biddulphieae Schütt.
      - *a.* Eucampiinae Schütt.
      - *b.* Triceratiinae Schütt.
      - *c.* Biddulphiinae Schütt.
      - *d.* Hemiaulinae Schütt.
    - 6. Euodieae Schütt.

KEY TO THE CENTRICAE.*

A. Valves with a concentric or radiating sculpture around a point or points, central or lateral, never arranged in relation to a middle line. Without raphe or pseudoraphe. Outline circular, oval, or elliptical, sometimes polygonal, rarely crescent-shaped or spindle-shaped. Processes common . . . Section **CENTRICAE.**

  I. Cells disc-shaped or cylindrical. Valves circular, their surface flat or convex, sometimes hemispherical. Valve sculpture arranged in relation to a central pole. Spines frequent. As a rule without horns or knobs; when present, small . . Subfamily **Discoideae.**

    1. Valves circular. Not divided into definite sectors by ribs, rays, or undulating sectors. Sculpturing sometimes arranged in bundles. Knobs or eyes absent; more or less long spines often present . Tribe **Coscinodisceae.**

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* Altered from Cupp (30, 1943, p. 34) to fit the Centricate genera of this region.

(*a*) Cells lens-shaped, round, or cylindrical. Usually united into more or less long typical chains. Intercalary bands often sculptured. Valve mantle usually strongly developed . . Subtribe **Melosirinae.**

Genera: *Melosira.*
Stephanopyxis.

(*b*) Cells short or elongated-cylindrical, bound into close chains by delicate siliceous projections or gelatinous threads. Cell wall usually weakly siliceous . . Subtribe **Skeletoneminae.**

Genera: *Skeletonema.*
Thalassiosira.

(*c*) Cells disc- or drum-shaped, usually solitary, very seldom bound in chains. Valve surface slightly convex, rarely strongly convex, sometimes nearly flat or slightly concave. Intercalary bands hyaline or rarely very delicately sculptured. Valve mantle not particularly well developed . . . . Subtribe **Coscinodiscinae.**

Genera: *Coscinodiscus.*
Planktoniella.
Actinocyclus.

2. Valves circular. Divided into distinct, complete or incomplete sectors by radial ribs or undulations or by wide hyaline rays from a characteristically constructed centrum. Without horns or prominent spines . . . . . Tribe **Actinodisceae.**

(*a*) Valves divided into sharply distinct sectors by radial ridges uniformly running from the margin to the hyaline central area. Small but distinct spines usually at the marginal ends of these ridges. Alternate sectors generally depressed . . . Subtribe **Actinoptychinae**

Genus: *Actinoptychus.*

(*b*) Valves sharply divided into sectors by broad hyaline rays running from a hyaline centre toward or to the margin, their outer ends marked with a minute spine; the hyaline centre divided into more or less wedge-shaped divisions confluent with the rays. Spaces between the radiating rays marked with fine, closely-set puncta arranged in radial or decussating rows . . Subtribe **Asterolamprinae.**

Genus: *Asteromphalus.*

II. Valves oval or circular in cross-section. Cells elongate, cylindrical or subcylindrical, with numerous intercalary bands, without internal septa. Valve structure arranged in relation to an excentric pole. Cells united into chains by their valves . . Subfamily **Solenoideae.**

3. As above . . . . . Tribe **Solenieae.**

(*a*) Valves flat or raised, with or without marginal spines. Excentric process or asymmetrical spine absent . Subtribe **Lauderiinae.**

Genera:
Corethron.
Schröderella.
Leptocylindrus.

(*b*) Valves with a single, often very short, spine or process, usually excentrically placed, thus destroying the symmetry of the cell. Valves flat or convex . Subtribe **Rhizosoleniinae.**

Genera:
Guinardia.
Rhizosolenia.

III. Cells box-shaped. Pervalvar axis generally shorter, sometimes slightly longer, than the valvar axis. Valves usually oval, sometimes polygonal, circular or semicircular; unipolar, bipolar, or multipolar, each pole represented by an angle or by a horn or spine, or by both angles and horns Subfamily **Biddulphioideae.**

4. Valves with long setae, longer than the cells. Cells united into chains by basal part of the setae. Seldom living as single cells. Intercalary

bands only seldom present. Valves circular or oval. All species pelagic	Tribe **Chaetocereae.**
Genera:	*Bacteriastrum.* *Chaetoceros.*
5. Horns short and thick or, if longer, with claws at the ends. United into chains by the ends of the horns. Valvar plane circular or elliptical, usually with one to several poles. Valves, therefore, elliptical to circular, two- to many-angled. Intercalary bands and septa often present. Live partly in plankton, partly littoral. Majority of species marine. Colony building in chains frequent . .	Tribe **Biddulphieae.**
(i) Knobs and horns without claws on the end . .	
(*a*) Valves bipolar. Cell wall weakly siliceous. Plankton forms . . .	Subtribe **Eucampiinae.**
Genera:	*Eucampia.* *Climacodium.* *Streptotheca.*
(*b*) Valves tripolar to multipolar, sometimes with bipolar varieties. Angles not bearing dome-like protrusions or horns. Intercalary bands frequently present. Marine forms, usually littoral, a few pelagic . .	Subtribe **Triceratiinae.**
Genus:	*Ditylum.*
(*c*) Valves bipolar, tripolar, or multipolar. Each angle with a dome-like protrusion or a horn. Usually strongly siliceous. Mostly large robust marine forms that build chains. Predominantly littoral, but sometimes pelagic. A few species are typically planktonic and are then more weakly siliceous . .	Subtribe **Biddulphiinae.**
Genus:	*Biddulphia.*
(ii) Horns with claws on the end.	

(*d*) Valves bipolar, tripolar, or quadripolar. Each angle with a long vertical horn tipped with a claw; or in the bipolar forms either as described or having the angles of only one valve turned vertically upward into short-pointed ends without claws . .	Subtribe **Hemiaulinae.**
Genus:	*Hemiaulus.*
6. Cells without horns. Valves without internal septa. Valves semicircular, broader than long. Intercalary bands very seldom present. Cells in girdle view cuneate . .	Tribe **Euodieae.**
Genus:	*Hemidiscus.*

SYSTEMATIC ACCOUNT OF THE CENTRICAE.

A. **CENTRICAE.**

I. **Discoideae.**

1. Coscinodisceae.

a. Melosirinae Schütt.

Genera: I. *Melosira.*
II. *Stephanopyxis.*

Genus I. **MELOSIRA** Agardh

(1, 1824).

Cells elliptical, circular or cylindrical, united in short chains by valve centres. Valves punctated. Intercalary bands none to numerous. Chromatophores numerous, small, plate-like. Nucleus central.

Species: *M. sphaerica.*

Species 1. **Melosira sphaerica** Karsten

(68, 1905, p. 70).

Cells united in short chains. Valves circular, in girdle view cylindrical, with no definite sculpturing. Diameter 54–65 μ, length of pervalvar axis 60 μ. Chromatophores several small plate-like bodies.

This may not be a true *Melosira.*

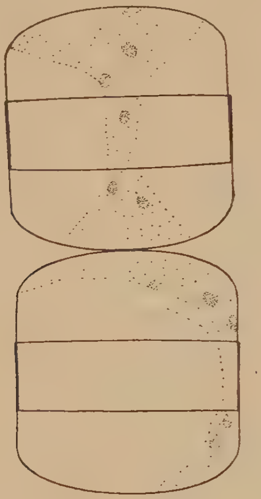

FIG. 1.—*Melosira sphaerica.* Diameter of cell 56 μ. Length of pervalvar axis 60 μ.

Genus II. **STEPHANOPYXIS** Ehrenberg
(37, 1844, p. 264).

Cells globoid or cylindrical with hemispherical valves. Form short chains with cytoplasm of adjacent cells in contact through stout, hollow spines situated on rounded ends and more or less parallel with pervalvar axis. Cell walls areolated. No intercalary bands. Small, round, numerous chromatophores. Resting spores noted.

Species: *S. turris.*
S. palmeriana.

Species 1. **Stephanopyxis turris** (Greville and Arnot) Ralfs
(99, 1861, p. 826).

Synonyms:

Creswellia turris Greville and Arnot (52, 1857, pl. xiv, p. 109), *Pyxidicula appendiculata* Ehrenberg (37, 1844, p. 85), *Stephanopyxis appendiculata* Ehrenberg (37, 1854, pl. 18, f. 4), *Creswellia turgida* Greville (53, 1859, p. 165), *Stephanopyxis cylindrica* Ehrenberg (37, 1873, p. 214), *Stephanopyxis niejahri* Ehrenberg (37, 1873, pl. 2, f. 1), *Stephanopyxis turgida* (Greville) Ralfs (99, 1861, p. 826).

Cells cylindrical with strongly convex valves. 10–28 spines at each end. Spines slightly thickened at tips, with a line of fusion midway between neighbouring cells. Coarse hexagonal areolations all about the same size arranged in rows parallel with pervalvar axis or oblique to it.

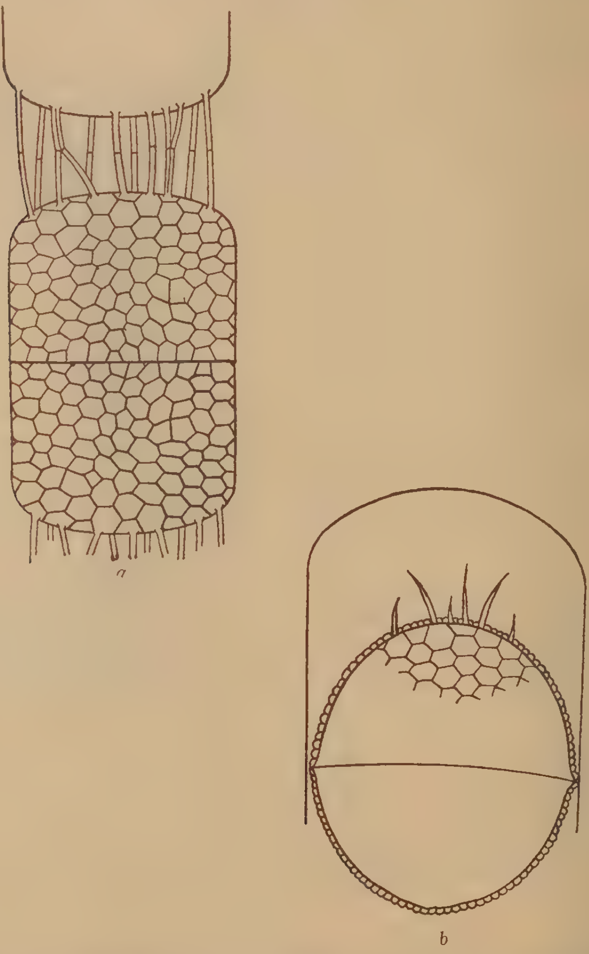

Fig. 2.—*Stephanopyxis turris.* *a.* Diameter of cell 42 μ. *b.* Resting spore.

About eight areolations in a row from valve margin to centre of cell in girdle view. Occasionally slightly constricted in valve mantle. Diameter of cell 36–57 μ. Resting spore with thick walls and strong spines.

A persistent form in the Cape West Coast Plankton has 12–14 equal areolations in a row from valve mantle to girdle zone. These are the same size as the areolations in the type, viz. 3½–4 in 10 μ. The pervalvar axis of this plant is longer and the apical axis shorter than in the type. Both forms appear in the same sample with no intermediate forms. Karsten (68, 1905, pl. 2, f. 1) figures a *Stephanopyxis* from the Antarctic which he designates *S. turris*. This form has 14 apparently smaller areolations in a row from girdle band to valve mantle. Lebour (73, 1930, p. 73) considers that this form with the finer more numerous equal areolations constitutes a separate species. Greville (53, 1859*a*, p. 165) established a species *Creswellia turgida* on forms found in Californian guano, which had finer, more numerous equal areolations. This species, later designated *S. turgida* (Grev.) Ralfs (99, 1861, p. 826), has since been absorbed in the synonymy of *S. turris*.

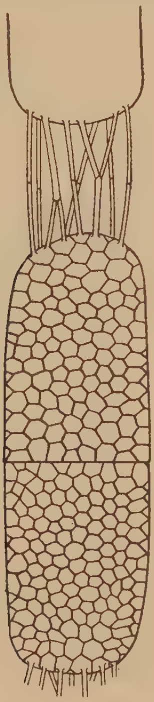

FIG. 3.—*Stephanopyxis turris*. Diameter of cell 36 μ.

Whether the form figured in fig. 3 is a separate species, as its presence in the same sample with the type would indicate, I hesitate to say. Karsten's figure may be of a form intermediate between the two which was not present in my material.

Species 2. **Stephanopyxis palmeriana** (Grev.) Grunow
(56, 1884, p. 38).

Synonyms: *Creswellia palmeriana* Greville (53, 1865*b*, p. 2).
Stephanopyxis campana Castracane (23, 1886, p. 88).

Cells cylindrical with rounded ends, similar in shape to *Stephanopyxis turris*. Form chains with cytoplasm of adjacent cells continuous through spines at ends of cells. Finer areolations than *S. turris*, and dwindling in size toward girdle line.

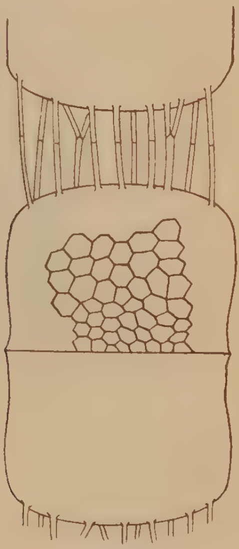

FIG. 4.—*Stephanopyxis palmeriana*. Diameter of cell 51 μ.

The constriction of the valve mantle is apparently of no specific significance. Cupp (30, 1943, p. 40) states that it is characteristic of *S. palmeriana*. Hendy (62, 1937, p. 237) quotes it as being characteristic of *S. turris*.

Many intermediate forms exist and the two species are easily confused, thus the distribution records are probably unreliable. The genus stands badly in need of revision and the literature is extremely confused.

b. Skeletoneminae Schütt.

Genera: I. *Skeletonema*.
II. *Thalassiosira*.

Genus I. **SKELETONEMA** Greville
(53, 1865*b*, p. 43).

Cells circular, cylindrical, or weakly spherical. Valves flat to strongly convex, without distinct sculpturing. Row of fine marginal spines parallel with longitudinal axis. The junction of these spines with those of the next cell unites the cells into chains. Cytoplasm of adjacent cells is in contact through these spines. Chromatophores one or two per cell. Nucleus central.

Species: *S. costatum.*

Species 1. **Skeletonema costatum** (Greville) Cleve
(24, 1878, p. 18).

Synonym: *Melosira costata* Greville (53, 1866, p. 66).

Cells circular, cylindrical, with rounded ends. Form long thin chains. Spines straight and slender. Space between cells usually longer than cells. Two chromatophores per cell. Nucleus central. Diameter of cell 3–16 μ.

Genus II. **THALASSIOSIRA** Cleve
(24, 1873*b*, p. 6).

Cells drum-shaped, united in flexible chains by a cytoplasmic thread. Occasionally solitary or embedded in an amorphous gelatinous mass. Valves flat, sometimes depressed in centre, delicately punctated. Marginal spinulae or spines present. Intercalary bands present. Numerous, small, plate-like chromatophores.

Species:

T. decipiens.
T. rotula.
T. condensata.
T. subtilis.
T. hyalina.
T. excentrica.

Key to Species.

A. One intercalary band.
  B. Valve structure very delicate, almost invisible.
    C. Striae punctate, very delicate, but arranged radially . . . *T. hyalina.*
    D. Punctation delicate, but in no particular order . . . *T. rotula.*
  B_1. Valves noticeably meshed.
    E. Marginal spinulae strongly curved, one apicule present . . . . *T. decipiens.*
    F. Marginal spinulae short, apicule lacking . . . *T. excentrica.*

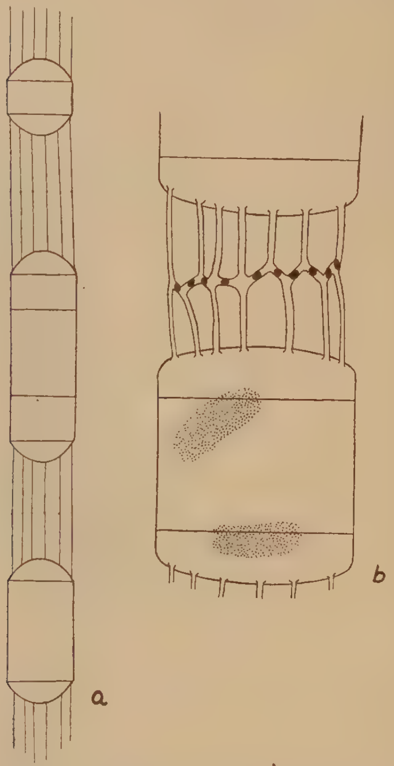

Fig. 5.—*Skeletonema costatum.* *a.* Part of chain, diameter 5 μ.
b. One cell, diameter 10·8 μ.

A_1. More than one intercalary band.
- G. Colonies united in chains . . . . . *T. condensata.*
- H. Colonies in gelatinous mass . . . . . . *T. subtilis.*

Species 1. **Thalassiosira decipiens** (Grunow) Jörgensen (67, 1905*c*, p. 96).

Synonyms:

Coscinodiscus excentricus Schmidt (103, 1874, pl. 3, f. 38), *C. excentricus* var.? *decipiens* Grunow (56, 1878, p. 125), *C. decipiens* Grunow (119, 1880, pl. 91, f. 10), *Thalassiosira gelatinosa* Hensen (63, 1887, p. 87), *C. excentricus* var. *gelatinosa* Cleve (24, 1897*a*, p. 23), *C. gelatinosus* Lemmerman (74, 1899, p. 266).

Cells drum-shaped, united in loose chains by cytoplasmic threads

30–80 μ in length. Occasionally in gelatinous irregular colonies. Valves slightly curved, with row of strong curved spines and one apicule. Sculpturing similar to *Coscinodiscus excentricus*. Diameter 12–40 μ. Numerous small chromatophores. One intercalary band per valve.

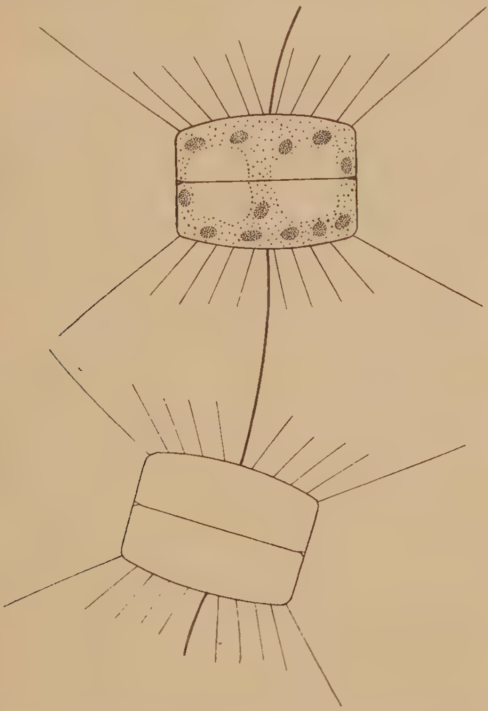

Fig. 6.—*Thalassiosira decipiens*. Part of chain, diameter 24 μ.

Species 2. **Thalassiosira rotula** Meunier

(84, 1910, p. 264).

Cells disc-shaped, united in chains by thick thread. Valves flat, rounded at margin. Delicate, regular punctation in no particular order. One unevenly thickened intercalary band per valve. Nucleus central. Numerous, small chromatophores. Diameter of cell 30–61 μ.

Species 3. **Thalassiosira condensata** Cleve

(24, 1900*a*, p. 22).

Cells somewhat rectangular in girdle view, valves circular, slightly depressed centrally, with single row of spinulae (sometimes with long

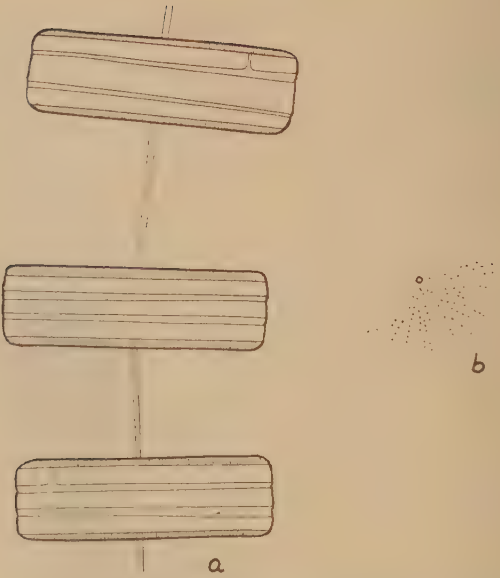

FIG. 7.—*Thalassiosira rotula.* *a.* Part of chain, diameter 42 μ.
b. Radiate punctation at valve centre.

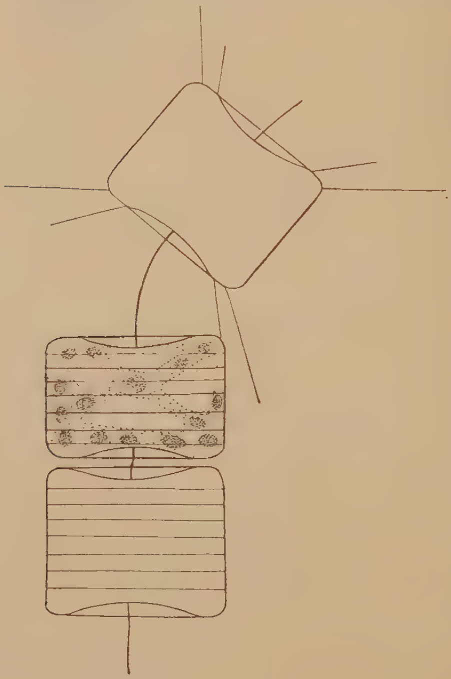

FIG. 8.—*Thalassiosira condensata.* Part of chain, diameter 31 μ.

radiating mucilage threads) directed obliquely outward. No visible sculpturing. United in chains by mucous thread. Numerous intercalary bands. Chromatophores numerous and plate-like. Diameter of cell 28–35 μ. Pervalvar axis 20–33 μ.

Species 4. **Thalassiosira subtilis** (Ostenfeld) Gran
(47, 1900*b*, p. 117).

Synonyms:

Podosira subtilis Ostenfeld (93, 1899, p. 35), *Cyclosira bergoni* Péragallo (97, 1897, p. 438).

Cells drum-shaped or box-like, embedded in a gelatinous mass. Numerous intercalary bands. Valves rounded with no distinct sculpture. Diameter of cell 16–32 μ.

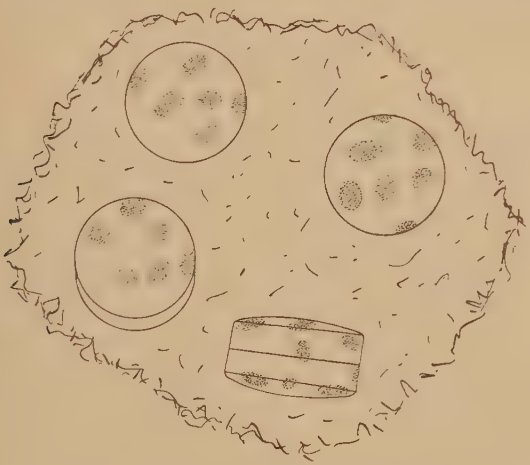

Fig. 9.—*Thalassiosira subtilis.* Part of colony, diameter of cells 18 μ.

Species 5. **Thalassiosira hyalina** (Grunow) Gran
(47, 1897*b*, p. 4).

Synonyms:

Coscinodiscus hyalinus Grunow (56, 1880, p. 113), *Thalassiosira clevei* Gran (47, 1897*a*, p. 29).

Cells discoid, united in chains by central mucous thread. Valves flat, somewhat rounded at edges, furnished with radial striae, single apicule, and single row of small spinulae at margin. Diameter 24–48 μ, pervalvar axis about 10 μ. Chromatophores 8–10 small plates.

Neritic. Reported as unusual off South African coast by Hendy.

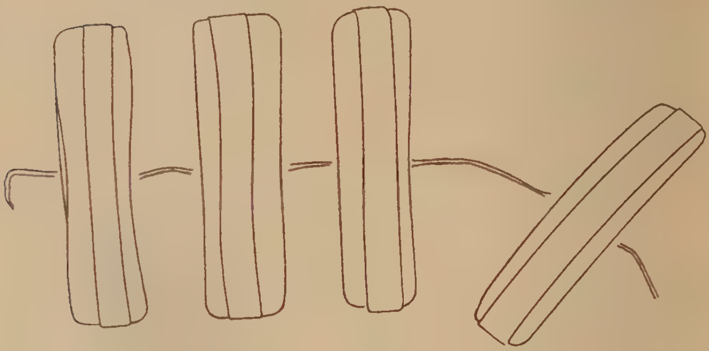

FIG. 10.—*Thalassiosira hyalina.* After Wilson in Lebour, 1930.

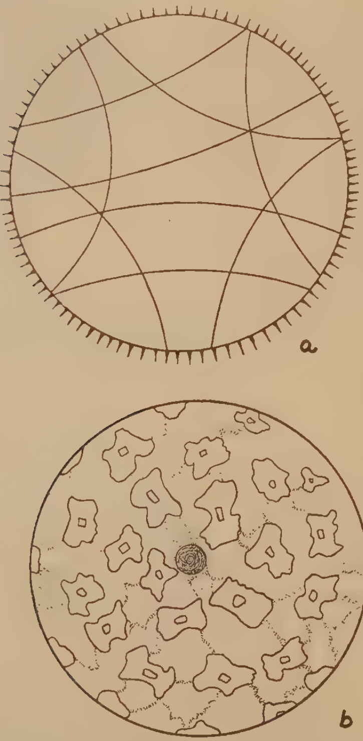

FIG. 11.—*Thalassiosira excentrica.* *a.* Valve view showing mesh plan. *b.* Valve view showing cell contents. Altered from Karsten, 1905.

Species 6. **Thalassiosira excentrica** Karsten (68, 1905, p. 73).

Cells discoid, united in chains by central mucous thread. Valve structure precisely the same as that of *Coscinodiscus excentricus*, furnished with short but fairly well-pronounced marginal spinulae. Diameter 34–40 μ. Chromatophores proportionally large, biscuit-formed, with a single pyrenoid. A series of cytoplasmic bands connects the chromatophores with each other and with the nucleus.

Reported as numerous in the phytoplankton by Karsten.

c. Coscinodiscinae Schütt.

Genera: I. *Coscinodiscus.*
II. *Planktoniella.*
III. *Actinocyclus.*

Genus I. **COSCINODISCUS** Ehrenberg (37, 1838, p. 128).

Pill-box cells usually single. Valves circular, finely punctated or hexagonally areolated and lacking large knobs or processes. In some species the areolations are more or less rounded and do not touch one another. Small marginal spinulae present or absent. Small apiculae (1 or 2) present or absent. If two are present they are asymmetrically situated. The central area of the valve may be smooth, sculptured, or with large areolae forming a rosette. Girdle is a single band to each valve. Intercalary bands often present. Numerous, small, plate-like chromatophores. Nucleus suspended in centre of cell by protoplasmic threads.

The genus has been divided into various groups by different authors, according to valve sculpture. Five main groups are represented here.

Key to Species.

Group 1. **Inordinati.** Valves with delicately, radially striated margins; otherwise, however, punctation is irregular . . .	*C. parvulus.*
Group 2. **Excentrici.** Valves flat or nearly so. Strongly hexagonally areolated. Areolations diminish in size from centre to periphery. Meshes curved and do not radiate from centre .	*C. excentricus.*
Group 3. **Lineati.** Valves usually flat. Hexagonally areolated. Areolations diminish slightly in size from centre to periphery. Meshes straight in tangential lines based upon six sectors. Spinulae or apiculi present or absent	*C. lineatus.*
Group 4. **Radiati.** Valves almost flat, convex or concave. Meshes radiate from centre but not in sectors. Tendency to dichotomy. Central rosette present or absent. Spinulae or apiculi present or absent.	

A. Valves flat, cells discoid.	
B. Central area or rosette lacking . . .	*C. radiatus.*
B_1. Central area or rosette present.	
C. Areolations equal in size . . .	*C. janischii.*
D. Areolations increase in size toward periphery	*C. gigas.*
A_1. Valves arched or concave.	
E. Valves convex, cells cuneiform in girdle view	*C. granii.*
E_1. Valves convex, cells symmetrical in girdle view	
F. Valve convex, centre slightly concave	*C. rotundus.*
G. Valves uniformly convex . .	*C. varians.*
Group 5. **Fasciculati.** Valves almost flat or slightly convex. Meshes radiate from centre in curved or straight radial sectors. Central rosette present or absent. Spinulae or apiculi present or absent.	
A. Central area present, spinulae lacking . . .	*C. curvatulus.*
B. Central area lacking, spinulae present . . .	*C. subtilis.*

GROUP I. INORDINATI.

Species I. **Coscinodiscus parvulus** Karsten
(68, 1905, p. 151).

Valves arched, with small "pearl-shaped" puncta scattered irregularly all over. Diameter 30 μ. Chromatophores small cocciform bodies.

Reported from this area by Karsten.

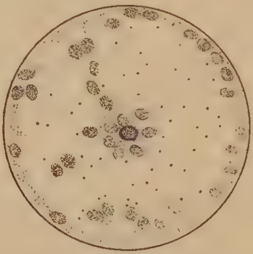

FIG. 12.—*Coscinodiscus parvulus.* Valve view. After Karsten, 1905.

GROUP 2. EXCENTRICI.

Species 2. **Coscinodiscus excentricus** Ehrenberg
(37, 1839, p. 146).

Synonyms:

Odontodiscus excentricus Ehrenberg (37, 1846, p. 79), *Coscinodiscus labyrinthus* Roper (102, 1858, p. 21), *Coscinodiscus minor* A. Schmidt (103, 1875, pl. 113, f. 9), *Thalassiosira excentrica* Cleve (24, 1903*b*, p. 216), *Coscinodiscus heliozoides* Siddal (111, 1912, p. 377).

Cells discoid, 50–90 μ in diameter. Valves flat. Hexagonally areolated. Central areola has seven areolae grouped around it. Areolae bigger near the centre than near the margins. Meshes curved and not radiating from the centre. Spinulae arranged in irregular circle.

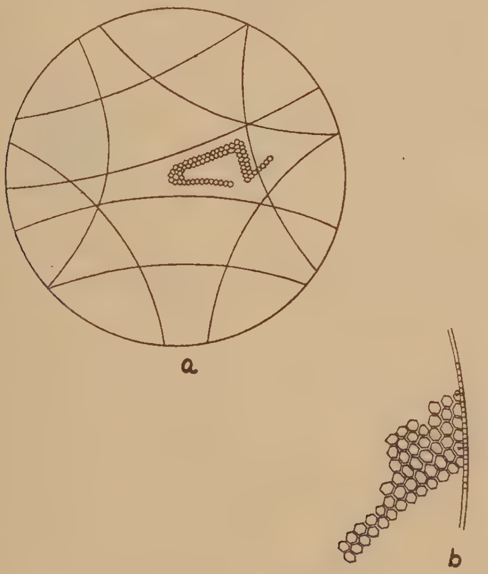

Fig. 13.—*Coscinodiscus excentricus.* *a.* Mesh plan, diameter of cell 59 μ. *b.* Areolation at margin.

GROUP 3. LINEATI.

Species 3. **Coscinodiscus lineatus** Ehrenberg (37, 1838, p. 129).

Synonyms:

Coscinodiscus ehrenbergi O'Meara (92, 1875, p. 264), *Coscinodiscus macraeanus* Grunow (103, 1875, pl. 59, f. 26), *Coscinodiscus lineatus* var. A. Schmidt (103, 1875, pl. 59, f. 31), *Coscinodiscus leptopus* Grunow (119, 1880, pl. 131, f. 5), *Coscinodiscus* spec. A. Schmidt (103, 1875, pl. 114, f. 13).

Cells discoid, 35–60 μ in diameter. Valves flat, hexagonally areolated. Areolae smaller near periphery than near the centre. Circular apertures

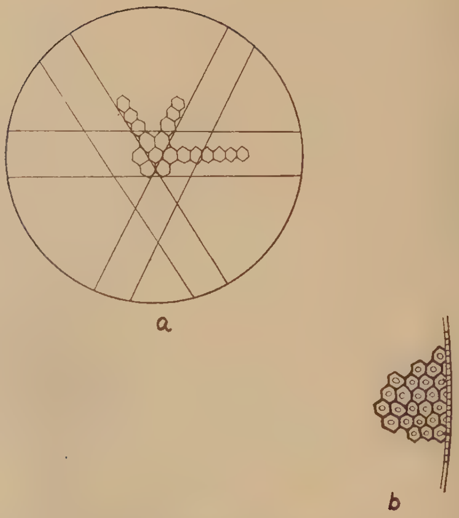

FIG. 14.—*Coscinodiscus lineatus.* *a.* Mesh plan, diameter of cell 42 μ. *b.* Areolation.

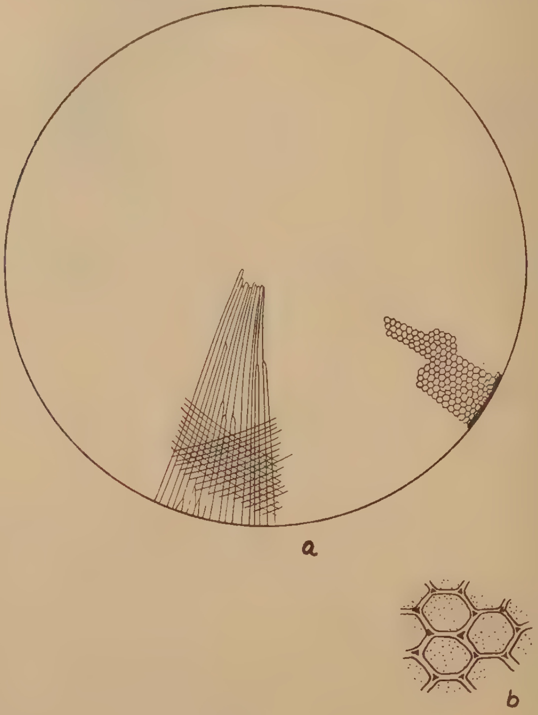

FIG. 15.—*Coscinodiscus gigas.* *a.* Mesh plan, diameter of cell 340 μ. *b.* Areolation.

of areolae usually distinct. Meshes straight in tangential lines based upon six sectors. Marginal spinulae present.

GROUP 4. RADIATI.

Species 4. **Coscinodiscus gigas** Ehrenberg
(37, 1841, p. 412).

Synonyms:

Coscinodiscus radiatus Bailey (7, 1842, XLII), *Coscinodiscus giganteus* Péragallo (97, 1878, p. 433).

Cells coin-shaped, weakly siliceous, diameter 300–500 μ. Valves flat, covered with radial areolation. Fairly large, irregular, hyaline area in centre. Areolae increase in size from centre to periphery. Numerous, small, rounded chromatophores.

Species 5. **Coscinodiscus radiatus** Ehrenberg
(37, 1839, p. 148).

Synonyms:

C. borealis Ehrenberg (37, 1861, p. 294), *C. fallax* Schumann (106, 1876, p. 62), *C. caspius* Ehrenberg (37, 1873, p. 394), *C. radiatus* f. *minor* A. Schmidt (103, 1875, pl. 3, f. 34), *C. radiatus* f. *parva* Grunow (56, 1878, p. 124), *C. radiatus* var. *subaequalis* Grunow (56, 1884, p. 20), *C. radiatus* var. *borealis* Grunow (56, 1884, p. 20), *C. radiatus* var. *media* Grunow (56, 1884, p. 20), *C. radiatus* var. *glacialis* Grunow (56, 1884, p. 20).

Cells coin-shaped, valves flat. Diameter 35–60 μ. Valves coarsely areolated, lacking rosette or central area. Areolae 3–4 in 10 μ in centre, 6–7 in 10 μ at margin. Radial rows distinct, secondary rows spiral, usually indistinct. Valve margin small.

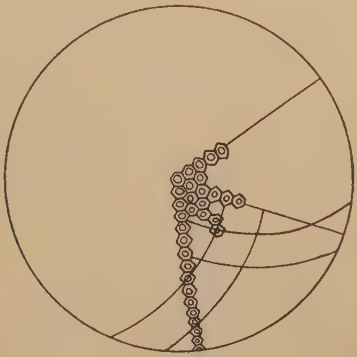

FIG. 16.—*Coscinodiscus radiatus.* Diameter of cell 42 μ.

Species 6. **Coscinodiscus janischii** A. Schmidt
(103, 1875, pl. 64, fs. 3, 4).

Synonym: *Coscinodiscus marginatus* Janisch (66, 1862, p. 3) (nec Ehrenberg).

Cells large, discoid. Irregularly hexagonal areolae, equal in size, arranged in radial rows. Regularity of hexagons deteriorates toward valve centre. Clear central area about $\frac{1}{10}$ total radius. Fascicules or wedges lacking but rows of single cells are regularly placed. Oblique rows less clear. Diameter 160–360 μ. Chromatophores irregular plates arranged on entire valve surface, each with one rectangular pyrenoid.

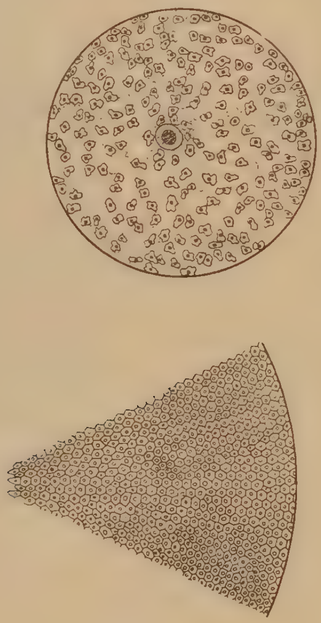

Fig. 17.—*Coscinodiscus janischii.* After Karsten, 1905.

Apparently a surface form, it occurs most abundantly in 10–20 m. near Capetown and elsewhere. Reported from this area by Karsten.

Species 7. **Coscinodiscus rotundus** Karsten
(68, 1905, p. 154).

Valves strongly convex, centres slightly concave. Radial rows run straight to the margin; similar to *Coscinodiscus convergens* but smaller.

Hexagonal areolations 10 in 10 μ at centre, 6 in 10 μ at half-radius. At margin very small, almost "pearl-shaped" hexagons. Diameter 78 μ. Chromatophores numerous cocciform bodies, mostly lying against the valves.

Described from this area by Karsten.

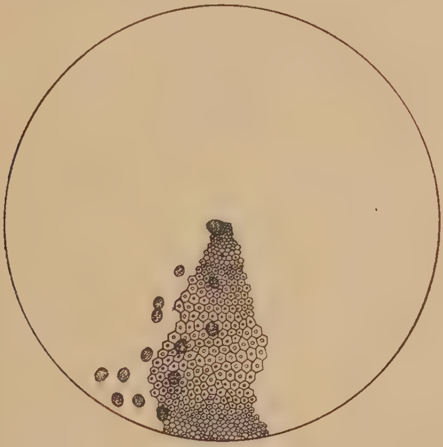

Fig. 18.—*Coscinodiscus rotundus.* Valve view. Partly after Karsten, 1905.

Species 8. **Coscinodiscus varians** Karsten
(68, 1905, p. 155).

Small form with convex valves. In valve view the central rosette is formed by a single, larger hexagon. Areolae in radiating rows, starting

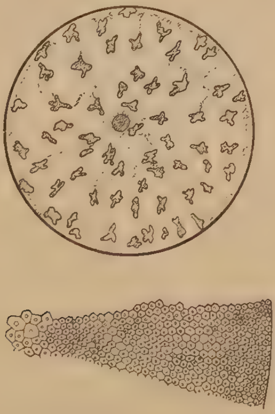

Fig. 19.—*Coscinodiscus varians.* After Karsten, 1905.

small but increasing considerably in size outward until at about half-valve radius the rows divide, after which the areolae are again smaller but increase in size toward the valve margin, where further division of the rows occurs with consequent diminution in size of areolae. Diameter 70–90 μ. Chromatophores oblong to biscuit-shaped, closely arranged on valve surface.

Described from this region by Karsten.

Species 9. **Coscinodiscus granii** Gough
(46, 1905, p. 338).

Synonyms:

Coscinodiscus concinnus Miquel (87, 1894, pl. 8, fs. 10, 13), *Coscinodiscus* sp. nov. Gough (46, 1903, p. 224).

Cells discoid in valve view, cuneiform in girdle view. Mesh consists of fine lines radiating from definite central rosette, secondary spiral rows distinct. Areolae diminish in size towards valve margin. Marginal spinulae, 5–7 μ apart, with distinct hyaline lines radiating from them toward the centre. Two asymmetrically placed apiculi on valve margin. Valves arched, centres excentric, girdle cuneate. Chromatophores numerous rounded bodies. Diameter 100 μ.

Neritic. Reported at two stations off South-West Africa by Hendy.

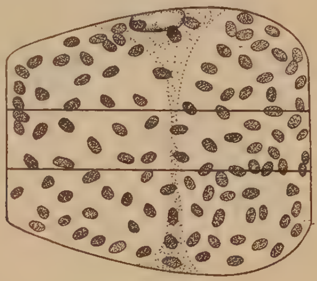

Fig. 20.—*Coscinodiscus granii.* Girdle view. After Gran and Angst, 1931.

Group 5. Fasciculati.

Species 10. **Coscinodiscus curvatulus** Grunow
(103, 1875, pl. 57, f. 33).

Synonyms:

Odontodiscus curvatulus Grunow (24, 1883*a*, p. 488), *Coscinodiscus curvatulus* var. *inermis* Grunow (56, 1884, p. 83), *Coscinodiscus curvatulus* var. *genuina* Grunow (56, 1884, p. 83).

Cells discoid, solitary. Valves almost flat, areolated. Meshes arranged in curved sectors. First curved line of each sector radiates from centre.

Other meshes of sector parallel with it. Central area surrounded by ring-like groove. No spinulae or apiculi. Diameter of valve 40–100 μ.

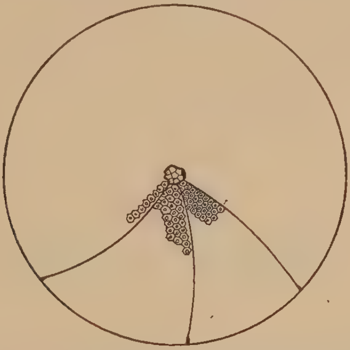

Fig. 21.—*Coscinodiscus curvatulus.* Diameter of cell 57 μ.

Species 11. **Coscinodiscus subtilis** Ehrenberg
(37, 1843*a*, p. 412).

Synonym: *Coscinodiscus normani* Gregory (52, 1859, p. 80).

Cells discoid. Valves thin, flat, with fine areolation. Central area and rosette lacking. Mesh consists of indistinct, radiating fascicules of

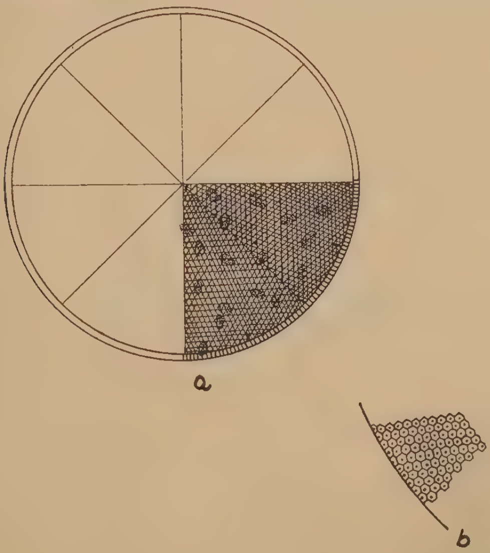

Fig. 22.—*Coscinodiscus subtilis.* *a.* Valve view showing mesh plan. *b.* Areolation at border. Altered from Karsten, 1905.

parallel lines crossed by more distinct oblique rays. Marginal spinulae present but indistinct. Girdle simple, striate, narrow. Chromatophores numerous plate-like bodies. Diameter 80–130 μ.

Neritic. Reported as occurring occasionally around the Cape of Good Hope by Hendy.

Genus II. **PLANKTONIELLA** Schütt
(93, 1893, p. 20).

Only species in this genus.

Species 1. **Planktoniella sol** (Wallich) Schütt
(93, 1893, p. 20).

Synonyms:

Coscinodiscus sol Wallich (103, 1860, p. 38), *Cestodiscus sol* Grunow (102, 1880, pl. 129, f. 6), *Planktoniella woltereckii* (Schimp.) Karsten (57, 1905, p. 157).

Cells coin-shaped, single, with a hyaline wing all around of extracellular chambers strengthened by radial rays. This expansion is weakly siliceous. Valves are flat and areolated like *Coscinodiscus excentricus*. Areolae are smaller near the margin. Numerous, small, plate-like chromatophores. Diameter of entire cell 50–165 μ.

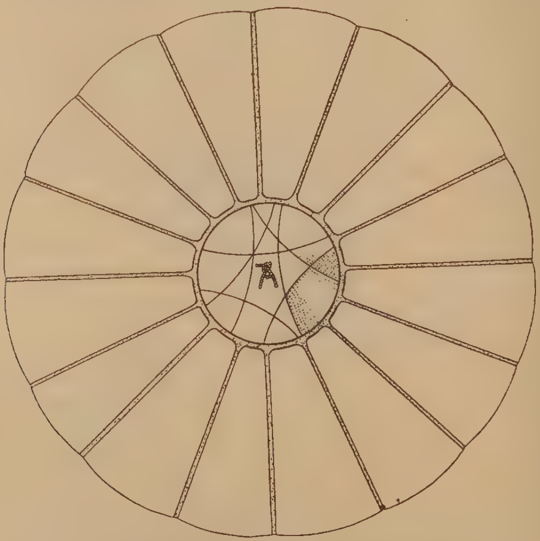

Fig. 23.—*Planktoniella sol.* Diameter of cell 83 μ.

Genus III. **ACTINOCYCLUS** Ehrenberg
(37, 1839, p. 171).

Cells solitary, *Coscinodiscus*-like. Valves with radial rows of points, marginal spinulae and one transparent "eye" near the margin inside the spinulae.

Species: *A. octonarius.*
A. rotula.

Species 1. **Actinocyclus octonarius** Ehrenberg
(37, 1839, p. 172).

Synonym: *Actinocyclus ehrenbergii* Ralfs in Pritchard (100, 1861, p. 834).

Cells discoid, valves convex, strongly rounded at margins, flattened in centre, thick-walled. Valve furnished with a crown of marginal spinulae from which run rows of puncta toward the centre, dividing the valve into radial compartments each containing a fascicule of radial lines of puncta. The dividing rows are surrounded by hyaline, interfascicular spaces. Marginal zone finely, radially striated. Girdle smooth, no intercalary bands. Diameter 170–220 μ. Chromatophores numerous, small plates.

Neritic, cosmopolitan. Reported here by Hendy.

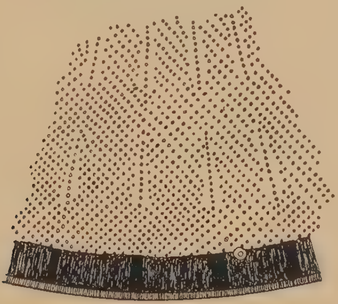

FIG. 24.—*Actinocyclus octonarius.* Portion of valve. Altered from Péragallo in Lebour, 1930.

This is the type-species of the genus. It was originally split into a number of species by Ehrenberg, which were later lumped by Ralfs (100, 1861, p. 834) under the title "*Actinocyclus ehrenbergii*" new species. The illegality of this was pointed out by Hendy (62, 1937, p. 263), who reinstated the present combination.

Species 2. **Actinocyclus rotula** Brun
(19, 1891, p. 6).

Cells discoid. Valves flat, divided into 12–16 segments by radial lines of granules, which terminate in apiculi at valve margin. Small central hyaline area present. Interstitial segments irregularly and sparsely punctate. Marginal zone strong, radially striate. Diameter 66 μ. Chromatophores numerous, small plates.

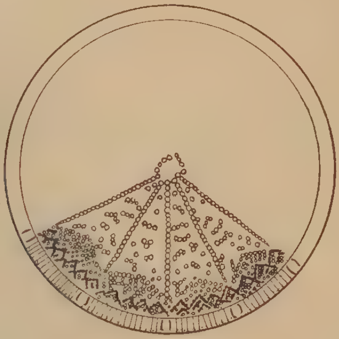

FIG. 25.—*Actinocyclus rotula.* Drawn from portion of photomicrograph in J. Brun, 1891.

Reported here by Hendy.

2. ACTINODISCEAE Schütt.
    a. Actinoptychinae Schütt.
        Genus: I. *Actinoptychus.*

Genus I. **ACTINOPTYCHUS** Ehrenberg
(37, 1841, p. 400).

Cells disc-shaped, solitary. Valve divided into alternately raised and depressed sectors. Smooth central field. No intercalary bands. One or more claw-like processes on outer margin of sectors, often only on raised ones.

Species: *A. senarius.*
A. splendens.
A. vulgaris.

Species 1. **Actinoptychus senarius** (Ehrenberg) Ehrenberg
(37, 1843*a*, pl. 1, f. 27).

Synonyms:

Actinocyclus senarius Ehrenberg (37, 1838, p. 172), *Actinocyclus undulatus* Kützing (70, 1844, p. 132), *Actinoptychus undulatus* (Bailey) Ralfs (100, 1861, p. 839), *Actinoptychus undulatus* Bailey (7, 1842, pl. 2, f. 11), *Actinoptychus biternarius* Ehrenberg (37, 1843*b*, p. 166), *Omphalopelta areolata* Ehrenberg (37, 1844, p. 270), *Actinoptychus omphalopelta* Grunow (56, 1868, p. 25), *Actinoptychus areolatus* A. Schmidt (103, 1875, pl. 1, f. 9), *Actinoptychus delectus* A. Schmidt (103, 1875, pl. 1, f. 8).

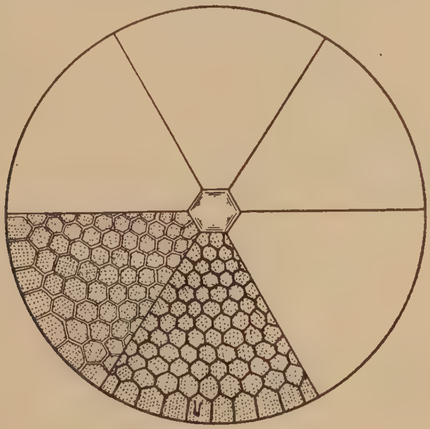

FIG. 26.—*Actinoptychus senarius.* Diameter of cell 72 μ.

Cells discoid, diameter 40–130 μ. Valves with six radial sectors, alternately raised and depressed. Irregular, coarse, polygonal areolation. Inner surface of areoles punctated. Smooth, hexagonal central field. Each raised sector, occasionally all the sectors, furnished with a stout apicule near the valve margin.

This is the type-species of the genus and is called *Actinoptychus undulatus* (Bailey) Ralfs by Hustedt (1930) and Cupp (1943), and *Actinoptychus undulatus* (Bailey) by Lebour (1930). However, Hendy (1937) points out that Ehrenberg's epithet claims priority.

Species 2. **Actinoptychus splendens** (Shadbolt) Ralfs ex Pritchard
(100, 1861, p. 840).

Synonyms:

Actinosphaenia splendens Shadbolt (108, 1854, p. 16), *Actinoptychus sedenarius* Ehrenberg (37, 1854, pl. 18, f. 26), *Actinoptychus quatuodrenarius*

Ehrenberg (37, 1854, pl. 18, f. 25), *Halionyx quinarius, senarius, octonarius, nonarius, denarius, undenarius, vicenarius* Ehrenberg (37, 1862, pp. 9–10), *Actinoptychus glabratus* Grunow (119, 1880, pl. 120, f. 6).

Cells discoid. Valves radially undulate, divided into 10–20 sectors. Nearly circular central area present. Valves coarsely, polygonally areolated. On each raised sector is a stout marginal apicule from which runs a hyaline line toward the central area. Each depressed sector has a narrow marginal hyaline band and lacks apiculi. Valve margin strongly striate. Diameter 120–140 μ. Chromatophores numerous, plate-like bodies.

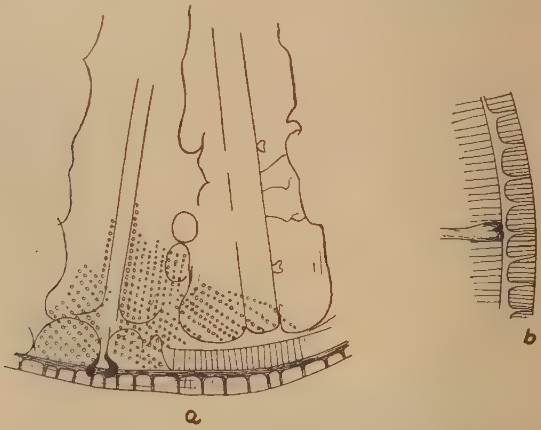

Fig. 27.—*Actinoptychus splendens.* *a.* Section of valve near margin. *b.* Section of margin. After Cupp, 1943.

Oceanic. Reported by Hendy as occurring rarely off the South African coast.

Species 3. **Actinoptychus vulgaris** Schumann
(106, 1867, p. 64).

Cells discoid. Valves divided into 6–20 sectors. Clear central area present. Mesh consists of a primary pattern of decussate rows of fine puncta over which is a more or less clear, coarse areolation. Margin clear and outer margin crenated. Diameter 64–116 μ. Chromatophores numerous, plate-like bodies.

Reported from this region by Karsten.

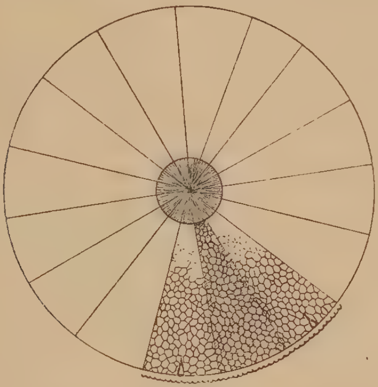

FIG. 28.—*Actinoptychus vulgaris.* Partly after Karsten, 1905.

b. Asterolamprinae Schütt.
Genus: I. *Asteromphalus.*

Genus I. **ASTEROMPHALUS** Ehrenberg
(37, 1844, p. 198).

Cells discoid or slightly oval, solitary. Valves flat to slightly convex, areolated. Central hyaline area with raised hyaline rays radiating from it. One ray narrower than the others.

Species: *A. heptactis.*
A. hookerii.

Species 1. **Asteromphalus heptactis** (Brébisson) Ralfs
(100, 1861, p. 838).

Synonyms:

Spatangidium heptactis Brébisson (16, 1857, p. 296), *Asterolampra heptactis* Greville (53, 1860*b*, p. 122), *Asteromphalus reticulatus* Cleve (24, 1873, p. 5), *Asteromphalus ornithopus* Karsten (68, 1905, p. 90), *Asteromphalus ralfsianus* Grunow (103, 1875, pl. 38, f. 5).

Cells solitary, slightly oval. Valves slightly convex. Seven rays of unequal length, with one long, narrow ray and three broader rays on either side. Hyaline area slightly excentric, diameter one-quarter to one-third that of diameter of valve. Diameter of valve 50–110 μ.

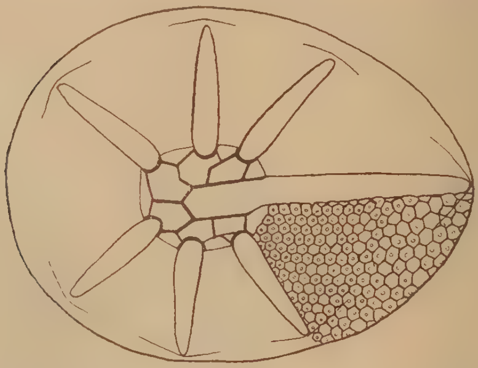

FIG. 29.—*Asteromphalus heptactis.* Diameter of cell 81 μ.

Species 2. **Asteromphalus hookerii** Ehrenberg (37, 1844, p. 200).

Synonyms:

Asteromphalus buchii Ehrenberg (37, 1844, p. 200), *Asteromphalus cuvierii* Ehrenberg (37, 1844, p. 200), *Asteromphalus humboldtii* Ehrenberg (37, 1844, p. 200), *Asterolampra hookerii* Greville (53, 1860*b*, p. 114), *Asteromphalus regularis* Karsten (68, 1905, p. 90), *Asteromphalus brookei* Bailey in (68, 1905, p. 90).

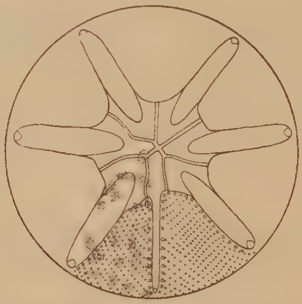

FIG. 30.—*Asteromphalus hookerii.* Partly after Karsten, 1905.

Cells discoid. Valves somewhat convex, undulate, divided into sectors by five to seven, narrow, hyaline rays. Hyaline central area about half total diameter. Sectors finely areolated. Central area marked by radiating branched lines. Diameter 44–60 μ.

Oceanic. Reported from this area by Karsten.

II. **Solenoideae** Schütt.
  3. SOLENIEAE Schütt.
    a. Lauderiinae Schütt.
      Genera: I. *Corethron.*
          II. *Schröderella.*
          III. *Leptocylindrus.*

Genus I. **CORETHRON** Castracane
(23, 1866, p. 85).

Cells solitary, cylindrical with rounded valves bearing a marginal crown of slender spines directed outwards at an angle. Numerous indistinct intercalary bands.

Species: *C. criophilum.*

Species 1. **CORETHRON criophilum** Castracane
(23, 1886, p. 85).

Synonyms:

Corethron hystrix Hensen (63, 1887, p. 89), *Corethron valdiviae* Karsten (68, 1905, p. 101), *Corethron inerme* Karsten (68, 1905, p. 104), *Corethron*

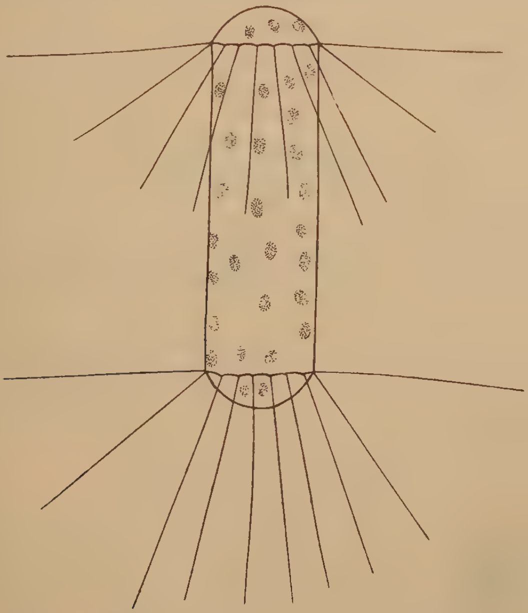

FIG. 31.—*Corethron criophilum.* Diameter of cell 22 μ.

murrayanum Castracane (23, 1886, p. 86), *Corethron pelagicum* Brun (19, 1891, p. 20), *Corethron hispidum* Castracane (23, 1886, p. 86).

Cell walls fairly thick. Valves strongly convex and furnished with a marginal circlet of well-developed spines. Intercalary bands very difficult to see. Numerous rounded, plate-like chromatophores.

Hendy 1937 lists the above synonyms for *C. criophilum.* He considers *Corethron* to be a monotypic genus with *C. criophilum* as the type-species. The other forms are not given the dignity of species but are considered as phases of the type-species, and are designated by the well-known epithets of the species which they replace. The close relationship of these forms, and indeed the synonymity of some, has been noted before by Ostenfeld 1902, Mangin 1915, Hustedt 1930, Gran and Angst 1931, and Hart 1934. Cupp 1943 did not use Hendy's terminology. The synonymy is quoted here although the term "phase" is not used in this report. The form occurred infrequently in these collections.

Genus II. **SCHRÖDERELLA** Pavillard

(95, 1913, p. 126).

Cells cylindrical. Valves flat to slightly convex, with concavity in the centre. A spine in this concavity unites with a corresponding spine of the adjacent cell. Valve margin armed with a crown of spinulae each with two gelatinous threads joining corresponding threads of adjacent cell. Numerous minutely punctated intercalary bands.

Species: *S. delicatula.*

Species 1. **Schröderella delicatula** (Péragallo) Pavillard

(95, 1913, p. 123).

Synonyms:

Lauderia delicatula Péragallo (96, 1888, p. 81), *Detonula delicatula* Gran (47, 1900*b*, p. 112), *Lauderia schröderi* Bergon (9, 1903*a*, p. 69), *Detonula schröderi* Gran (47, 1905, p. 22), *Schröderella schröderi* (Bergon) Pavillard (95, 1925, p. 23).

Cells cylindrical, united in dense rigid chains. Valves flat to slightly convex with depression in centre. Diameter of cell 18–30 μ. Mantle surface delicately areolated. Numerous collar-like intercalary bands.

Genus III. **LEPTOCYLINDRUS** Cleve

(24, 1889, p. 54).

Cells long, cylindrical, united by whole valve surface to form chains. Valves flat, unarmed. Intercalary bands difficult to see. Cell walls thin, hyaline. One to many chromatophores.

Species: *L. danicus.*

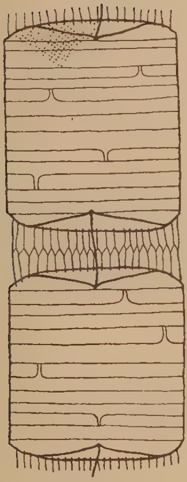

Fig. 32.—*Schröderella delicatula.*
Diameter of cell 21·6 μ.

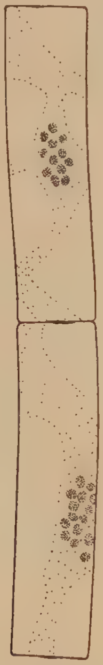

Fig. 33.—*Leptocylindrus danicus.*
Diameter of cell 10·6 μ.

Species 1. **Leptocylindrus danicus** Cleve
(24, 1889, p. 54).

Cells cylindrical, 6–12 μ in diameter, 2–10 times as long. Long stiff chains, often only one cell wall between two valves. Chromatophores numerous. Intercalary bands very difficult to see.

b. Rhizosoleniinae Schütt.
Genera: I. *Guinardia.*
II. *Rhizosolenia.*

Genus I. **GUINARDIA** H. Péragallo
(96, 1892, p. 107).

Cells cylindrical, longer than broad. Solitary or in chains. Intercalary bands numerous, collar-like. Valves circular, flat. A small, rudimentary spine is placed asymmetrically at the valve margin. Numerous chromatophores. Nucleus in central cytoplasm.

Species: *G. flaccida.*
G. blavyana.

Species 1. **Guinardia flaccida** (Castracane) H. Péragallo (96, 1892, p. 107).

Synonyms:

Eucampia striata var. *maxima* Stolterfoth (114, 1879, p. 825), *Rhizosolenia ? flaccida* Castracane (23, 1886, p. 74), *Pyxilla baltica* Hensen (63, 1887, p. 87), *Rhizosolenia castracane* Cleve (24, 1889, p. 2), *Henseniella baltica* Schütt (33, 1894, p. 1425), *Guinardia baltica* Schütt (107, 1896, p. 84).

Cells cylindrical, solitary or in chains. Valves slightly concave with asymmetrical, rudimentary tooth at margin. Diameter of cell 30–90 μ. Numerous narrow intercalary bands. Cell wall very weakly siliceous. Numerous chromatophores, usually stellate but frequently rounded.

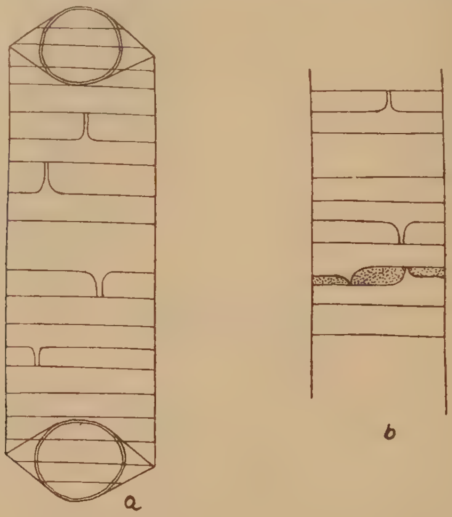

Fig. 34.—*Guinardia flaccida.* *a.* Single cell, diameter 70·2 μ. *b.* Junction of cells in chain.

Species 2. **Guinardia blavyana** H. Péragallo (96, 1892, p. 107).

Synonym: *Guinardia blavyana* var. *conspicua* Péragallo (96, 1892, p. 107).

Cells solitary or united in chains of two or three. Collar-like intercalary bands with overlapping angular ends. Chromatophores discoid, each with a pyrenoid. Nucleus central, with radiating cytoplasmic threads.

Reported from here by Karsten, who considers the nature of the intercalary bands places the species near "Dactyliosolen".

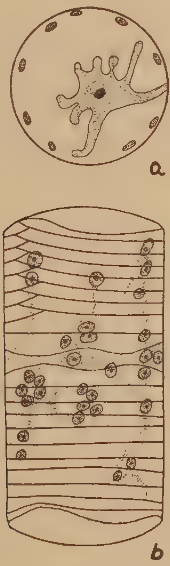

FIG. 35.—*Guinardia blavyana.* *a.* Cell with nucleus. *b.* Cell showing contents. After Karsten, 1905.

Genus II. **RHIZOSOLENIA** (Ehrenberg) Brightwell

(18, 1858*a*, p. 93).

Cells cylindrical, elongated pervalvar axis. Usually straight, sometimes curved. Solitary or in chains. Valves circular or elliptical, with an excentric apex or process which fits into a corresponding trough on the adjacent cell. Intercalary bands very numerous but sometimes difficult to see. Chromatophores usually numerous. Several species have a tendency to dimorphism, e.g. *R. alata.* These forms are considered by different authors as different species or as forms of the same species. Hendy (1937) reduces them to synonyms and regards them as "phases" of the same species.

The genus is subdivided according to the form of the valve and the intercalary bands. Pavillard's (1925) scheme is followed here.

Key to Species.

Group 1. **Inermes.** Valves more or less conical, truncated, without terminal spine. Scales as in Genuinae	*R. alata.*
Group 2. **Affines.** Valves rounded, not conical, furnished with a short spine. Intercalary bands collar-like.	
A. Cells straight.	
B. Chromatophores small, numerous; valves irregularly arched	*R. fragilissima.*
C. Chromatophores few, large; valves flat . . .	*R. delicatula.*
A_1. Cells curved	*R. stolterfothii.*
Group 3. **Robustae.** Valves elongated and conical. Extremity more or less thickened with a variably shaped spine. Intercalary bands collar-like	*R. robusta.*
Group 4. **Imbricatae.** Two rows of lateral scale-like intercalary bands. Suture lines zigzag when spine is dorsal	*R. imbricata.*
Group 5. **Genuinae.** Two rows of dorsi-ventral scale-like intercalary bands.	
A. Two wing-like expansions at base of spine . .	*R. styliformis.*
B. Wing-like expansions lacking	*R. hebetata.*
Group 6. **Squamosae.** Intercalary bands numerous, imbricated scales .	*R. simplex.*

Group 1. Inermes.

Species 1. **Rhizosolenia alata** Brightwell (18, 1858*a*, p. 96).

Cells cylindrical, straight. Valves conical, narrowing suddenly to a tube-like, more or less curved, oblique process. At the base of the tube

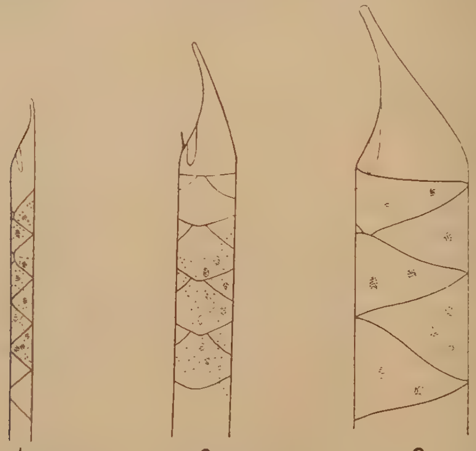

Fig. 36.—*a*. *Rhizosolenia alata.* Diameter of cell 9 μ. *b*. form "gracillima." Diameter of cell 5 μ. *c*. form "indica." Diameter of cell 32 μ.

is a depression into which the apex of the adjacent cell fits. Intercalary bands scale-like, rhombic, in two dorsi-ventral rows, finely striated. Cell wall thin, weakly siliceous. Chromatophores numerous, small. Diameter of cell 7–15 μ.

Form "**gracillima**" (Cleve) Grunow (119, 1880, pl. 79, f. 8).

Synonym: *Rhizosolenia* (*alata* var.?) *gracillima* Cleve (24, 1881, p. 26).

Structurally similar to type but very much narrower. Diameter of cell 4–7 μ.

Form "**indica**" (Péragallo) Ostenfeld (93, 1901*b*, p. 160).

Synonyms:

Rhizosolenia indica Péragallo (96, 1892, p. 116), *Rhizosolenia quadriiuncta* Péragallo (96, 1892, pl. 5, f. 17), *Rhizosolenia alata* var. *corpulenta* Cleve (24, 1897*a*, p. 24).

Structurally similar to type but having a very much greater diameter. Diameter of cell 20–60 μ.

GROUP 2. AFFINES.

Species 2. **Rhizosolenia delicatula** Cleve (24, 1900, p. 28).

Cells cylindrical, with flat valves slightly rounded on margins. Closely set, straight chains. Valve armed with a short excentric spine fitting into the margin of the neighbouring cell. Chromatophores few, large. Diameter of cell 10–12 μ.

Species 3. **Rhizosolenia stolterfothii** H. Péragallo (96, 1888, p. 82).

Synonyms:

Eucampia striata Stolterfoth (114, 1878, p. 835), *Pyxilla stephanos* Hensen (63, 1887, p. 88).

Cells cylindrical, united in curved chains. Valves flat, armed with a strong spine visible only at the free ends. Intercalary bands collar-like, numerous, usually easily seen. Chromatophores small, numerous. Diameter of cell 15–45 μ.

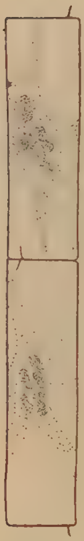

FIG. 37.—*Rhizosolenia delicatula.* Diameter of cell 16 μ.

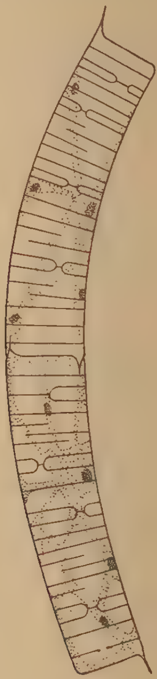

FIG. 38.—*Rhizosolenia stolterfothii.* Diameter of cell 27 μ.

Species 4. **Rhizosolenia fragilissima** Bergon (9, 1903*a*, p. 49).

Synonyms:

Rhizosolenia cylindrus Ostenfeld (93, 1899, p. 55), *Leptocylindrus danicus* Schütt (107, 1900, p. 504), *Rhizosolenia delicatula* Gran (47, 1902, p. 172), *Rhizosolenia delicatula* Ostenfeld (93, 1903, p. 568, f. 123), *Rhizosolenia faeroëensis* Ostenfeld (93, 1903, p. 568, f. 124), *Rhizosolenia pellucida* Schröder (104, 1911, p. 631, f. 6).

Cells cylindrical, 8–70 μ in diameter, ends rounded, united in short straight chains. In the centre of the valve is a short spine fitting into a corresponding depression on the adjacent cell. Collar-like intercalary bands, cell wall weakly siliceous. Chromatophores numerous, small plates.

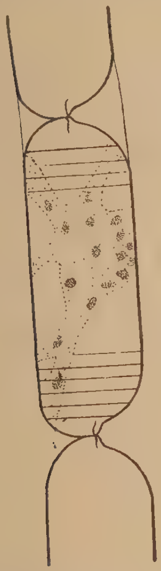

FIG. 39.—*Rhizosolenia fragilissima.* Diameter of cell 13·5 μ.

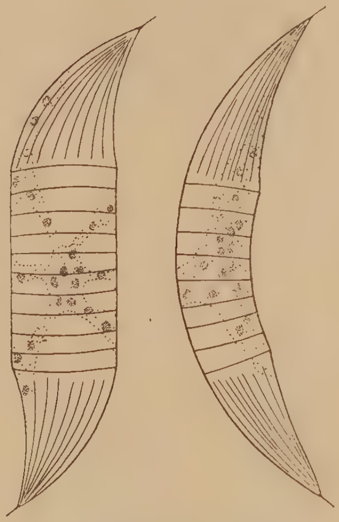

FIG. 40.—*Rhizosolenia robusta.* Diameter of cell 55 μ.

GROUP 3. ROBUSTAE.

Species 5. **Rhizosolenia robusta** Norman
(99, 1861, p. 866).

Synonym: *Rhizosolenia sigma* Schütt (107, 1893, p. 22).

Cells cylindrical, with deeply conical, curved valves. Valvar plane elliptical. Small, hollow, apical process with short spine. Cells usually single, crescent- or **S**-shaped. Diameter of cell 50–400 μ. Intercalary bands numerous, collar-like. Chromatophores numerous.

GROUP 4. IMBRICATAE.

Species 6. **Rhizosolenia imbricata** var. **shrubsolei** (Cleve)
Schröder (104, 1906*a*, p. 346).

Synonyms:

Rhizosolenia shrubsolei Cleve (24, 1881, p. 26), *Rhizosolenia atlantica* Péragallo (96, 1892, p. 114), *Rhizosolenia pacifica* Péragallo (96, 1892, fs. 6, 7).

Cells cylindrical, single or in chains. Valves oblique, pointed, with apical process hollow nearly all the way up, with small wings at the base which run up about a third of the spine and do not extend to the valve. Intercalary bands scale-like in two long rows, each band being a triangular scale with the corner pointing upwards so that they form an imbricating row on each side of the apex. The bands have striations formed of minute puncta. Chromatophores numerous, small. Diameter of cell 12–22 μ.

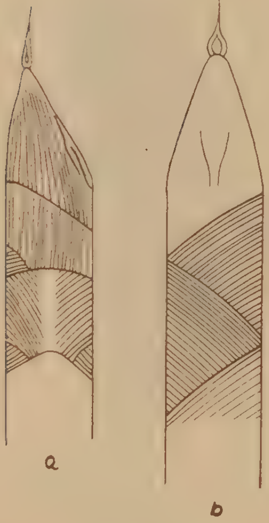

Fig. 41.—*Rhizosolenia imbricata* var. *shrubsolei*. *a*. Side view of cell, diameter 18 μ. *b*. Ventral view of cell.

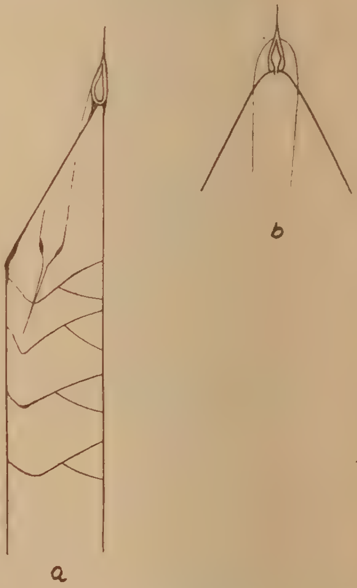

Fig. 42.—*Rhizosolenia styliformis*. *a*. Side view of cell, diameter 77 μ. *b*. Ventral view of end of cell.

Group 5. Genuinae.

Species 7. **Rhizosolenia styliformis** Brightwell (18, 1858*a*, p. 95).

Cells cylindrical. Valves obliquely pointed as in *R. imbricata* var. *shrubsolei*, but more sharply. Valve process pointed, hollow, with cavity penetrating valve. Two wing-like processes begin on the valve and finish near the base of the process. Valve has a groove for the spine and wings of the adjacent cell. Intercalary bands scale-like with reticulated sculpturing. Very numerous chromatophores. Diameter of cell 40–100 μ.

Species 8. **Rhizosolenia hebetata** (Bailey) Gran emend (47, 1904, p. 524).

This is a dimorphic species. Occasionally a cell exhibits a different form at each end.

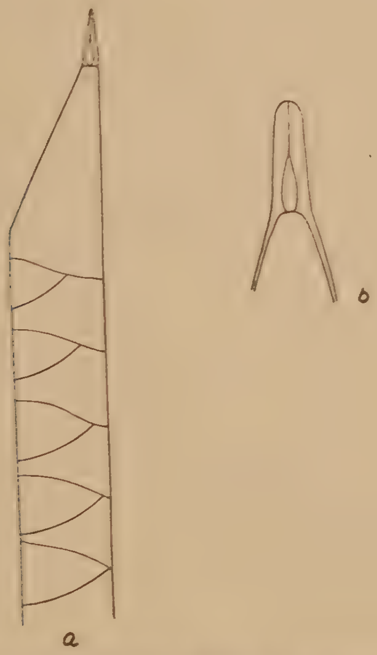

FIG. 43.—*Rhizosolenia hebetata* form *hiemalis*. *a*. Part of cell, diameter 18 μ.
b. Spine.

Form "**hiemalis**" Gran (47, 1904, p. 527).

Synonyms:

Rhizosolenia hebetata Bailey (8, 1856, p. 5), *Rhizosolenia hebetata* var. *subacuta* Grunow (56, 1884, p. 527).

Cells straight, valves drawn out longitudinally. Thick, solid, apical process with small, hollow, rounded spine. Intercalary bands distinct. Cell wall strongly siliceous. Chromatophores small, numerous. Diameter of cell 18–20 μ.

Form "**semispina**" (Hensen) Gran (47, 1905, p. 55).

Synonym: *Rhizosolenia semispina* Hensen (63, 1887, p. 84).

Cells cylindrical, valves drawn out, armed with long, curved, hair-like spine. Similar to form "hiemalis" but smaller in diameter, 5–12 μ, and more weakly siliceous. Imbrications more delicate in structure.

Occurs infrequently in the northern part of this area.

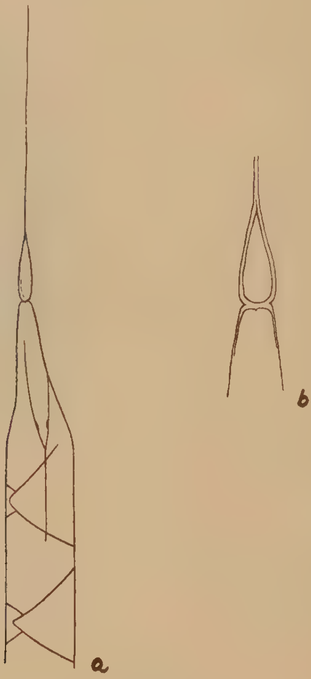

FIG. 44.—*Rhizosolenia hebetata* form *semispina*. *a*. Cell in ventral view. *b*. Base of spine.

GROUP 6. SQUAMOSAE.

Species 9. **Rhizosolenia simplex** Karsten (68, 1905, p. 95).

Cells small, cylindrical, straight. Valve deeply conical, with slender spine hollow at the base. Intercalary bands small, squamose, scale-like. Cell wall very weakly siliceous, imbrications very difficult to see. Chromatophores numerous cocciform bodies, arranged along cell wall and around nucleus. Diameter 10–26 μ. Length 200–400 μ.

Oceanic. Reported by both Karsten and Hendy as being fairly common in this area.

III. **Biddulphioideae** Schütt.
4. CHAETOCERAE Schütt.
Genera I. *Bacteriastrum.*
II. *Chaetoceros.*

Genus I. BACTERIASTRUM Shadbolt
(108, 1854, p. 14).

Cells cylindrical. Valves armed with marginal bristles. The fusion of the bristles of one cell with those of the next forms loose chains. The bristles of neighbouring cells are fused for a certain length outside the base and then bifurcate. Terminal bristles often curved in valve view, not fused and therefore not forked. Pavillard revised the genus 1924–25.

GROUP 1. ISOMORPHA.

Terminal setae of like construction and form on both ends of the chain. Terminal setae directed either outward or toward the centre of the chain.

GROUP 2. SAGITTATA.

Terminal setae on either end of the chain different in form and direction. Setae of posterior valve directed outward from chain and running nearly parallel with chain axis. Setae of anterior valve curved toward inner part of chain, or deviating little from valvar plane.

Species: *B. hyalinum.*

GROUP I. ISOMORPHA.

Species 1. Bacteriastrum hyalinum Lauder
(71, 1864, p. 6).

Synonyms:

Bacteriastrum spirillum Castracane (23, 1886, pl. 29, f. 1), *Bacteriastrum varians* var. *borealis* Ostenfeld (93, 1901*a*, p. 293), *Bacteriastrum minus* Karsten (68, 1905, p. 171).

Cells not much longer than broad. Chain straight or slightly curved. Apertures narrow but distinct. Number of inner setae per valve 7–25. Bifurcations parallel with chain axis. Terminal setae curved and bent toward chain centre. Chromatophores numerous, small. Diameter of cell 13–56 μ.

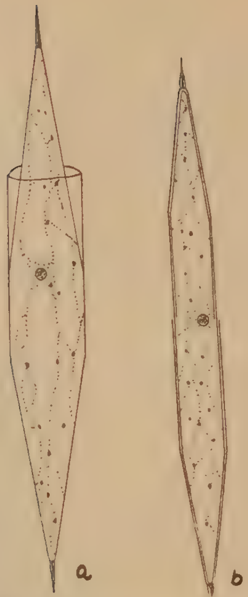

FIG. 45.—*Rhizosolenia simplex*. After Karsten, 1905.

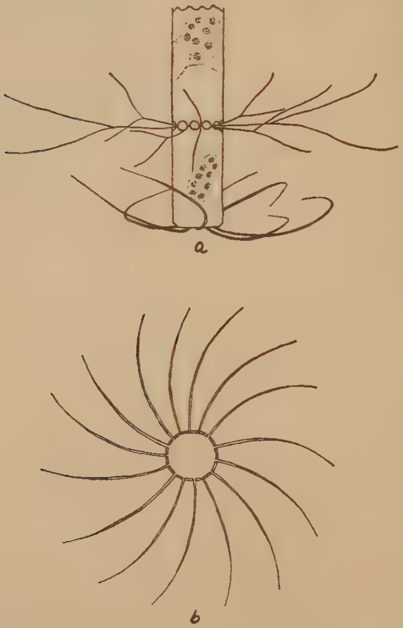

FIG. 46.—*Bacteriastrum hyalinum*. *a*. End of chain. Diameter of cell 23 μ.
b. Valve view of terminal cell.

Genus II. **CHAETOCEROS** Ehrenberg (37, 1844).

Cells oval to nearly circular in valve view. Quadrangular in broad girdle view. Occasionally solitary, usually united by setae into long or short chains. Valve surface flat with setae on the pointed ends of the ellipse. These setae cross the setae of the adjacent cell and fuse firmly. Cells separated by large or small apertures or foramina. Special end cells bear the terminal setae which are usually shorter and thicker. Cell wall formed of two valves and one or two girdle bands. Intercalary bands sometimes present but usually difficult to see. One to several, small or large, chromatophores. Pyrenoids sometimes visible. Resting spores formed in most neritic species. The valves of the spores are often armed with spines or spicules.

The genus is subdivided as follows:

Sub-genus 1. PHAEOCEROS Gran (47, 1897*a*).

Large, robust species. Chromatophores numerous, globoid, and penetrating into setae.

Sec. 1. **Atlantica** Ostenfeld (93, 1903).

Direction of all setae alike in one plane, except terminal setae which differ from others. Small spine usually present in centre of valve.

1. *C. atlanticum.*

Sec. 2. **Borealia** Ostenfeld (93, 1903).

Setae usually diverging in all directions, the directions on one valve often differing from those on the other. Usually no spine in centre of valve.

2. *C. peruvianus.*
3. *C. convolutum.*

Sub-genus 2. HYALOCHAETE Gran (47, 1897*a*).

Chromatophores one or several plates, more seldom numerous granules. Setae usually thin without chromatophores in them. Chiefly neritic. Resting spores known in most of the species.

A. *Each cell with more than two chromatophores.*

Sec. 1. **Oceanica** Ostenfeld emen. Lebour (73, 1930).

Chromatophores rather large, 6–10. Setae fused along a short portion of their length. No resting spores known. Oceanic.

4. *C. decipiens.*

Sec. 2. **Dicladia** (Ehrenberg) Gran emen. Lebour (73, 1930).

Like *Oceanica*, but with setae not always fused for a portion of their length. Resting spores with two horns armed with small branches on primary valves. Neritic.

5. *C. capense.*
6. *C. lorenzianus.*
7. *C. tetras.*

Sec. 3. **Cylindrica** Ostenfeld (93, 1903).

Valves nearly circular. Apertures very narrow. Chromatophores small, numerous. Terminal setae not thicker than others. Resting spores about the middle of the cells, smooth or with spines.

8. *C. teres.*

Sec. 4. **Compressa** Ostenfeld (93, 1903).

Cells compressed. Terminal setae little different from others. Inner setae of two forms: thinner normal setae, and intercalary thickened and twisted ones. Chromatophores numerous. Resting spores smooth or with a row of spicules.

B. *Each cell with one or two chromatophores.*

Sec. 5. **Protuberantia** Ostenfeld (93, 1903).

Two chromatophores, each with a large pyrenoid situated in a protuberance in the middle of the valve surface. Resting spores with two long horns.

9. *C. didymus.*
10. *C. strictum.*

Sec. 6. **Constricta** Ostenfeld (93, 1903).

Chromatophores one or two. Cells more or less constricted. Girdle at least one-third the length of the cell. Terminal setae mostly thicker than the others. Resting spores about the middle of the cell and with numerous spines on both valves.

11. *C. vanheurckii.*
12. *C. constrictus.*

Sec. 7. **Stenocincta** Ostenfeld (93, 1903).

One chromatophore. Girdle narrow, not one-third the length of the cell. Apertures rather narrow. Terminal setae rather thicker than others, curved and for the most part diverging greatly. Resting spores about the middle of the cell and with numerous spines on both valves.

Sec. 8. **Laciniosa** Ostenfeld (93, 1903).

Chromatophores one or two. Girdle rather long. Apertures rather large. Terminal setae rather thicker than others, not diverging greatly. Resting spores smooth or with minute spines on primary valve, not in the middle of the cell.

Sec. 9. **Diadema** (Ehrenberg) Ostenfeld emen. Gran (47, 1905).

One chromatophore. Chains long with conspicuous terminal setae. Primary valve of resting spore with branched process or crown of spines or sometimes smooth. Occasionally both valves armed.

13. *C. seiracanthus.*
14. *C. subsecundus.*
15. *C. difficile.*

Sec. 10. **Diversa** Ostenfeld (93, 1903).

Short rigid chains. Inner setae of two kinds. Terminal setae less spread out than a special pair of setae in middle of cell. One chromatophore.

16. *C. messanensis.*

Sec. 11. **Brevicatenata** Gran (47, 1905).

One or two chromatophores. Short straight chains, few joints. Terminal setae very thin, more or less different from others. Mostly small to very small forms.

Sec. 12. **Curviseta** Ostenfeld emen. Gran (47, 1905).

One chromatophore. Setae curved, all bent in one direction. Chains usually curved, without special end cells.

17. *C. curvisetus.*

Sec. 13. **Anastomosantia** Ostenfeld (93, 1903).

Setae united by a bridge.

Sec. 14. **Furcellata** Ostenfeld (93, 1903).

One chromatophore. Terminal setae not differentiated. Resting spores excentrically arranged in mother cell, lying close together, two and two, with thick fused setae; with smooth valves or with short spines.

Sec. 15. **Socialia** Ostenfeld (93, 1903).

Chains curved, embedded in mucilage, forming irregular spherical colonies. One chromatophore. Resting spores smooth or with small spines.

18. *C. socialis.*

Sec. 16. **Simplicia** Ostenfeld (93, 1903).

Cells living singly or two or three together.

19. *C. gracilis.*
20. *C. parallelis.*

Sub-genus 1. PHAEOCEROS.

Sec. 1. .. ATLANTICA.

Species 1. **Chaetoceros atlanticum** Cleve (24, 1873*b*, p. 11).

Synonyms:

Chaetoceros dispar Castracane (23, 1886, p. 76), *Chaetoceros audax* Schütt (107, 1895, p. 47), *Chaetoceros polygonum* Schütt (107, 1895, p. 46).

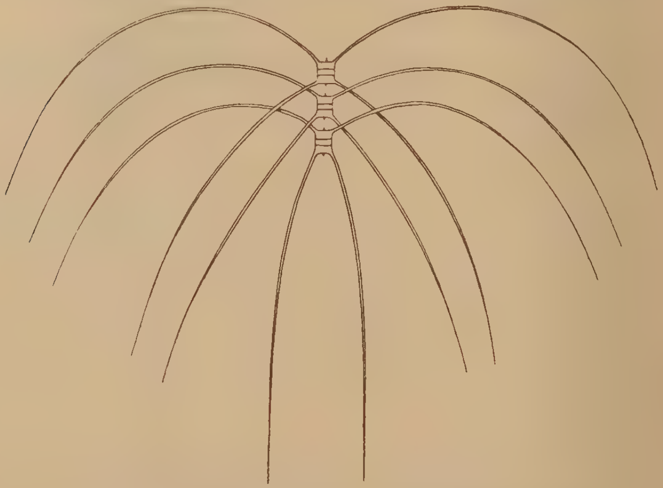

Fig. 47.—*Chaetoceros atlanticus.* After Karsten, 1905.

Chains straight, flat, 15–40 μ broad. Valves elliptical, furnished with small central spine. Apertures hexagonal, large. Setae have narrow base just inside cell corner, thicken suddenly and taper slowly further out. Distinct constriction between low valve mantle and girdle zone. Terminal setae shorter and thicker than others, directed outward at base and bent towards pervalvar axis further out. Chromatophores numerous, small rounded bodies, penetrating the setae.

Oceanic. Identified in this region by both Hendy and Karsten.

Variety **"neapolitana"** (Schröder) Hustedt (65, 1927, p. 645).

Synonym: *Chaetoceros neapolitanum* Schröder (53, 1900, p. 29).

Cells similar to type but much narrower, 8–12 μ. Valves elliptical, central spine difficult to see. Setae similar to type but run parallel with pervalvar axis for short distance before turning outward to cross setae of neighbouring cells. Apertures oblong to diamond-shaped. Chromatophores as in type.

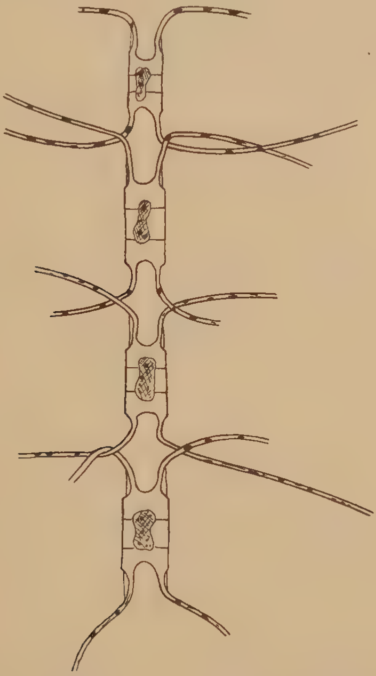

FIG. 48.—*Chaetoceros atlanticus* var. *neapolitana*. Chain in broad girdle view. After Cupp, 1943.

Oceanic, temperate form. Reported by Hendy as occurring frequently in this area.

Sec. 2. BOREALIA.

Species 2. **Chaetoceros peruvianus** Brightwell
(18, 1856, p. 107).

Synonyms:

Chaetoceros peruvianus var. *currens* Péragallo (97, 1897, pl. 125, f. 2), *C. convexicornis* Mangin (81, 1919, p. 3), *C. peruvianus* var. *currens* Forti (41, 1922, p. 149).

Cells usually solitary, occasionally in short chains. Upper valve rounded, lower flat. Setae of upper valve originate near centre, turn sharply, and run backward in outwardly convex curves. Setae of lower valve originate near margin, outwardly slightly convex, run more parallel with pervalvar axis than those of upper valve. Setae thick and armed with strong spines.

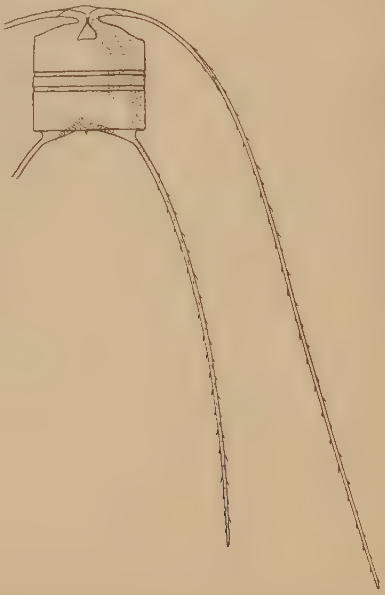

FIG. 49.—*Chaetoceros peruvianus.* Diameter of cell 22 μ.

Species 3. **Chaetoceros convolutum** Castracane
(23, 1886, p. 78).

Synonyms:

Chaetoceros brightwellii Gran (47, 1897, p. 11) (nec Cleve), *Chaetoceros criophilus* Cleve (24, 1901, p. 20).

Cells united in chains 15–30 μ broad, curved or slightly twisted. Valves unequal, upper one arched, lower flat. Valve mantle almost as deep as girdle zone, definite constriction at junction of two. Setae arise at centre of upper valve, at corners of lower, bend toward one end of chain, and are armed with small spines. Chromatophores numerous, small, rounded bodies.

Reported as very common by Hendy.

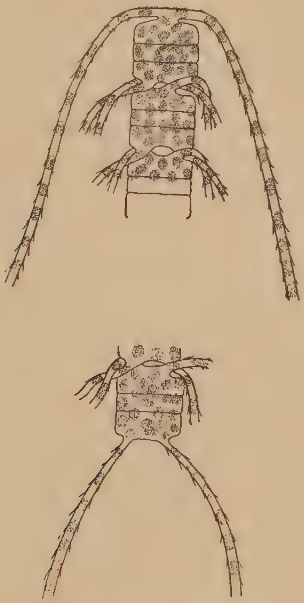

FIG. 50.—*Chaetoceros convolutom.* Chain in broad girdle view. Partly after Gran and Angst, 1931.

Sub-genus 2. **HYALOCHAETE.**

Sec. 1. OCEANICA.

Species 4. **Chaetoceros decipiens** Cleve (24, 1873*b*, p. 11).

Synonyms:

Chaetoceros concretus Engler (38, 1883, p. 11), *Chaetoceros grunowii* Schütt (107, 1895, p. 43), *Chaetoceros decipiens* f. *singularis* Gran (47, 1904, p. 536).

Cells rectangular in broad girdle view, 10–80 μ broad. Corners of cells touch those of next cell forming long, straight, stiff chains. Apertures

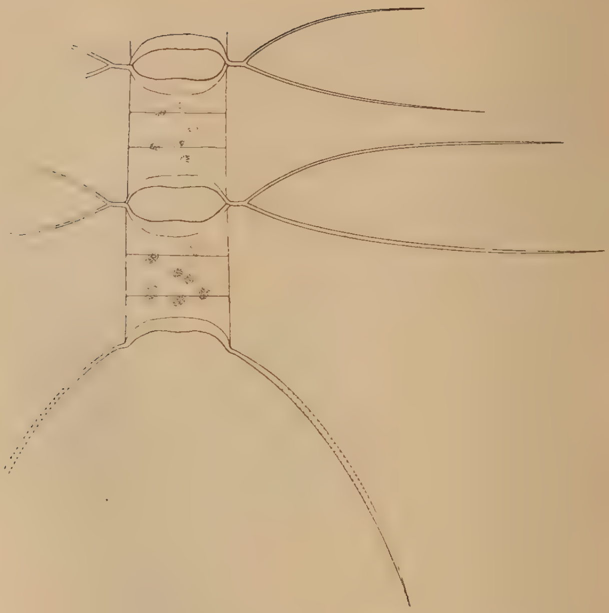

FIG. 51.—*Chaetoceros decipiens.* Diameter of cell 22 μ.

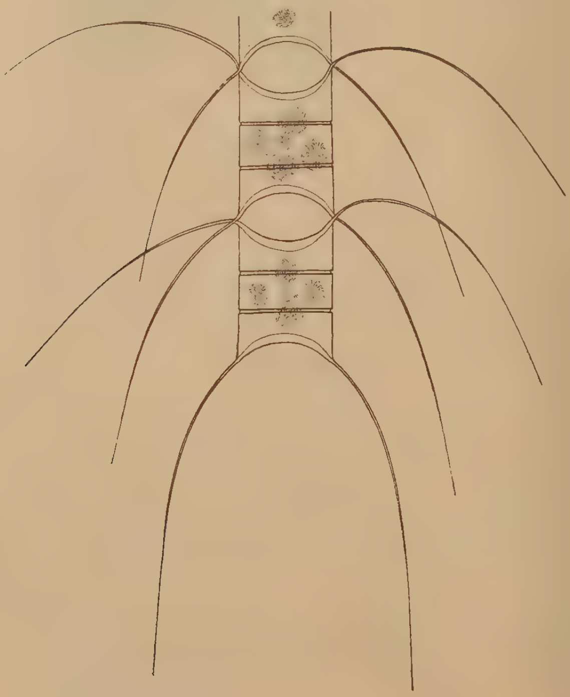

FIG. 52.—*Chaetoceros capense.* Apical axis 13 μ.

vary in size and shape. Setae originate at cell corners, directed perpendicular to chain axis. Fused for a length 2–3 times the diameter of the setae. Terminal setae shorter and thicker, first directed outward and then bending to become nearly parallel with chain axis. Setae have no particular sculpturing. Occasionally heavily punctated like *Chaetoceros lorenzianus*. Chromatophores 4–10 per cell.

Sec. 2. DICLADIA.

Species 5. **Chaetoceros capense** Karsten
(68, 1906, p. 167).

Cells small, valves elliptical, apical axis 10–18 μ. Valve surface concave. Long thin setae originate at corners. United to form chains, 4–8 cells per chain. Valve mantle deep. Sharp constriction at girdle zone. Chromatophores 4 irregular plates.

Species 6. **Chaetoceros lorenzianus** Grunow
(56, 1863, p. 157).

Synonym: *Chaetoceros cellulosum* Lauder (71, 1864, p. 78).

Cells rectangular in girdle view. Apertures polygonal to elliptical. Setae fused only at point of exit from margin, strongly punctate. Terminal setae divergent for entire length. Chromatophores large, plate-like, 4–10 per cell. Diameter of cell 20–50 μ.

Species 7. **Chaetoceros tetras** Karsten
(68, 1905, p. 167).

Form with a high girdle zone, 2–3 times higher than valve, with a slight constriction between valve mantle and girdle zone. Valves similar to each other, slightly concave, with slight convexity in centre. Anterior terminal valve furnished with stronger convexity, posterior terminal valve more strongly concave. Apertures elliptical, narrowed in the centre. Setae slender, short, directed outward. Anterior terminal setae stronger, directed parallel with pervalvar axis. Posterior terminal setae considerably stronger, directed downward. Occasional adjacent pairs of setae, stronger than the others, are also directed downward. Chromatophores usually four, plate-like, each with a pyrenoid. In the young cells of this form there are only two chromatophores, which divide immediately.

Described from Capetown by Karsten.

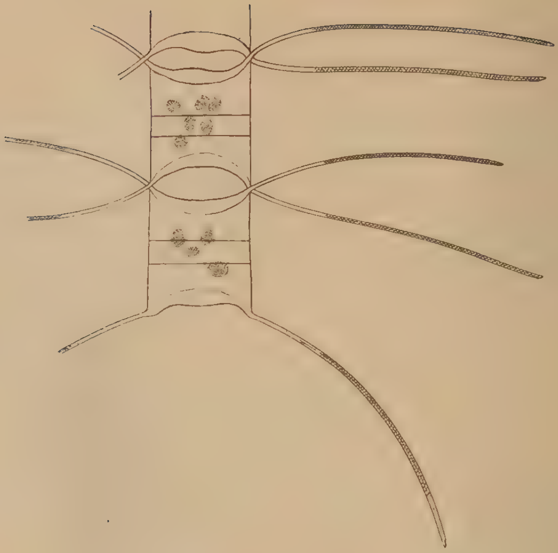

FIG. 53.—*Chaetoceros lorenzianus.* Diameter of cell 31 μ.

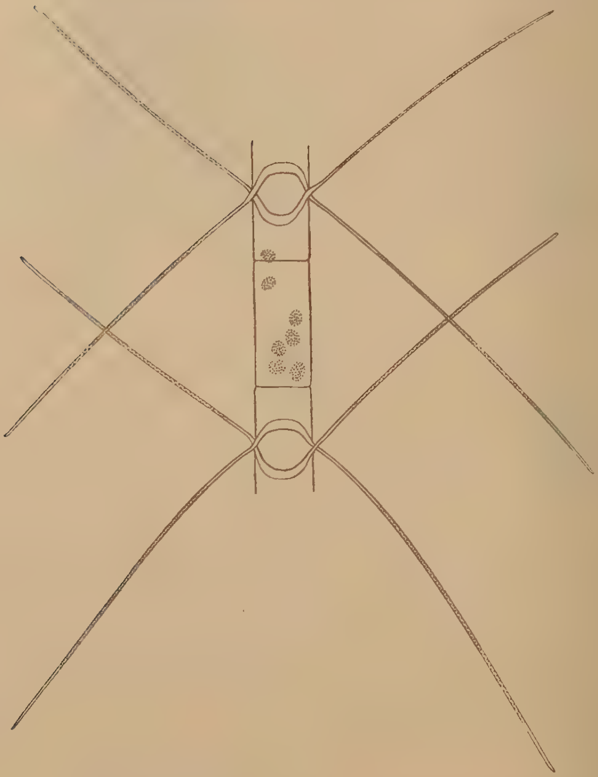

FIG. 54.—*Chaetoceros lorenzianus.* Diameter of cell 12·6 μ.

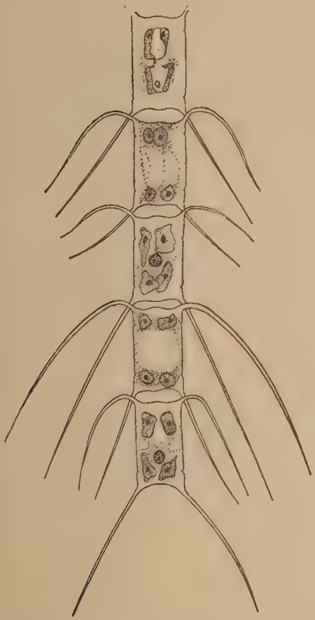

Fig. 55.—*Chaetoceros tetras.* Chain showing cell contents. After Karsten, 1905.

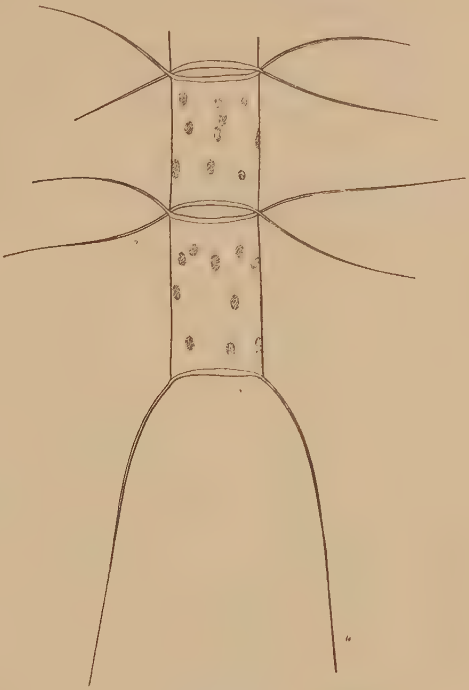

Fig. 56.—*Chaetoceros teres.* Diameter of cell 19·2 μ.

Sec. 3. Cylindrica.

Species 8. **Chaetoceros teres** Cleve
(24, 1896*b*, p. 30).

Cells cylindrical, 18–48 μ in diameter. Rectangular in broad girdle view with sharp corners, longer than broad. Apertures very narrow. No constriction between low valve mantle and high girdle zone. Setae originate at cell corners and extend perpendicular to chain axis. Numerous small chromatophores. Numerous intercalary bands invisible in water mounts.

Sec. 5. Protuberantia.

Species 9. **Chaetoceros didymus** Ehrenberg
(37, 1846, p. 75).

Synonyms:

Goniothecium gastridium Ehrenberg (37, 1845*b*, p. 82), *Chaetoceros gastridium* Ehrenberg (37, 1846, p. 76), *Chaetoceros mamillanum* Cleve (24, 1889, p. 55), *Chaetoceros protuberans* Schütt (5, 1901, p. 41), *Chaetoceros didymus* var. *hiemalis* Tempère and Péragallo (117, 1907), *Chaetoceros didymus* var. *genuina* Gran and Yendo (49, 1914, p. 12).

Chains straight, cells compressed in broad girdle view, with concave end surfaces, and a semicircular knob in the centre. Length of apical axis 10–40 μ. Setae arise at cell corners and cross at base or further out. Two chromatophores per cell, each with a pyrenoid located in the protuberance.

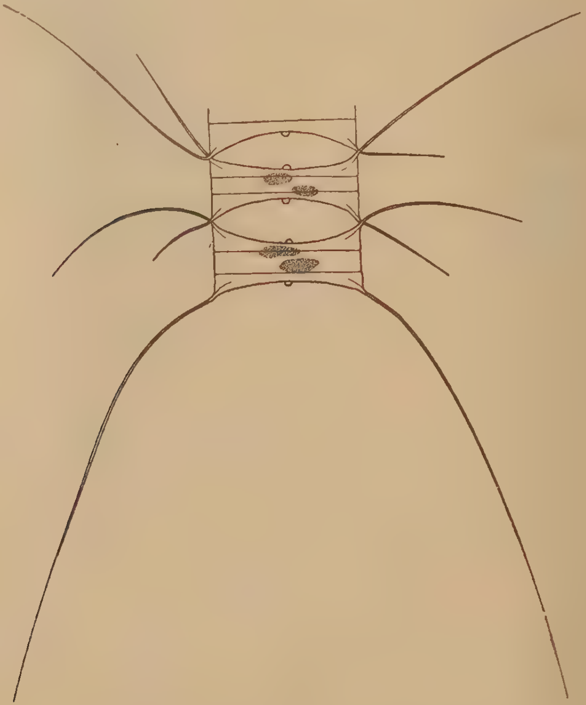

Fig. 57.—*Chaetoceros didymus.* Diameter of cell 21 μ.

Variety "**protuberans**" (Lauder) Gran and Yendo
(49, 1914, p. 12).

Synonyms:

Chaetoceros protuberans Lauder (71, 1864, pl. 8, f. 11), *Chaetoceros didymus* Okamura (91, 1907, p. 95).

Similar to type. Terminal setae more strongly divergent than in type, convex toward outside, usually thicker than other setae. Inner setae usually cross further out than in type.

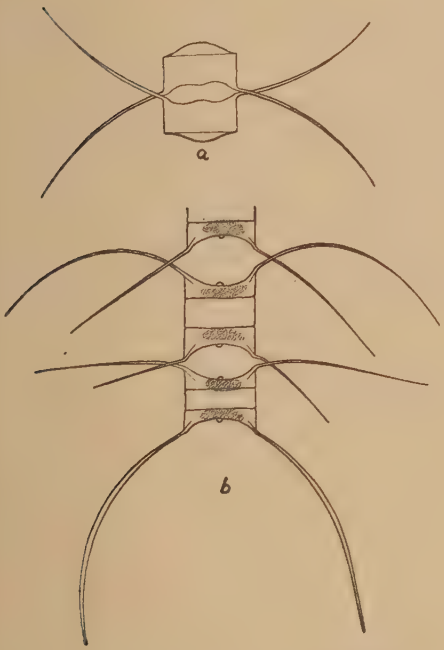

Fig. 58.—*Chaetoceros didymus.* *a.* Resting spore. *b.* var. "*protuberans.*" Diameter of cell 32 μ.

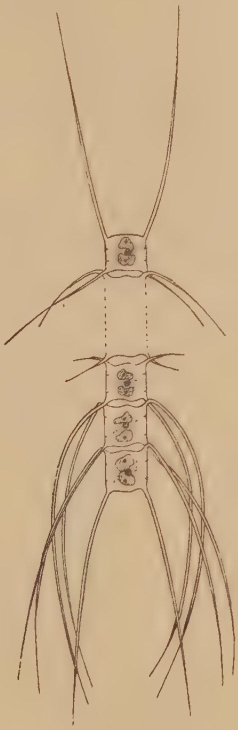

Fig. 59.—*Chaetoceros strictum.* Part of chain with cell contents. Partly after Karsten, 1905.

Species 10. **Chaetoceros strictum** Karsten (68, 1905, p. 168).

Cells rectangular in broad girdle view, valves similar, elliptical. Slight constriction at junction of valve mantle and girdle zone. Terminal setae at both ends of the colony strongly developed and running parallel with pervalvar axis. The remaining setae are all bent sharply toward the one end. In this formation they vary, some being poorly developed, others bending strongly toward the terminal setae. Two plate-like chromatophores with small pyrenoids.

Described from this area by Karsten.

Sec. 6. CONSTRICTA.

Species 11. **Chaetoceros vanheurckii** Gran (47, 1897, p. 18).

Synonyms:

Chaetoceros ralfsii van Heurck (119, 1880, pl. 82B/3), *Chaetoceros constrictum* Gran (50, 1930).

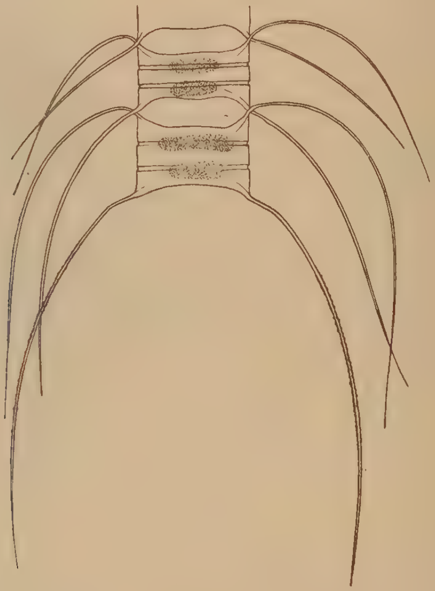

FIG. 60.—*Chaetoceros vanheurckii.* Diameter of cell 18 μ.

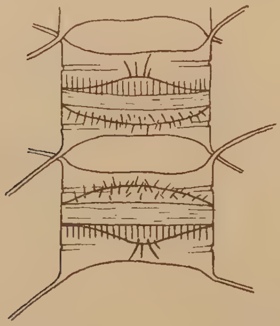

FIG. 61.—*Chaetoceros vanheurckii.* Resting spores.

Cells rectangular in broad girdle view, 14–36 μ broad. United in short chains. Apertures lanceolate. Valves flat to slightly concave. Setae slender. Terminal setae strong with spinules in spirals. Chromatophores two per cell. Resting spores armed with short spines. Set of parallel spines on valve rim.

Species 12. **Chaetoceros constrictus** Gran
(47, 1897*a*, p. 17).

Cells 12–35 μ wide, rectangular in broad girdle view, with sharp corners. Marked constriction between valve and girdle zone. Valves concave, raised slightly in centre. Setae with no basal part. Terminal setae acutely divergent. Chromatophores two per cell.

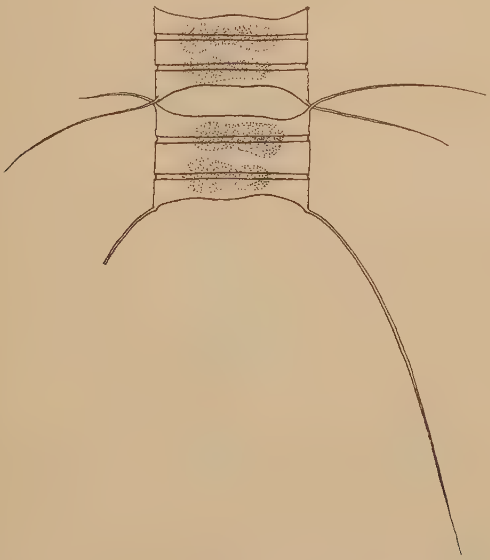

Fig. 62.—*Chaetoceros constrictus.* Diameter of cell 16·5 μ.

Sec. 9. Diadema.

Species 13. **Chaetoceros seiracanthus** Gran
(47, 1897*a*, p. 21).

Cells rectangular in girdle view. Valves fairly flat. Apertures long, oval. One chromatophore per cell, attached to broad side of girdle. Setae arise at cell corners, directed transverse to base. Terminal setae diverge at an acute angle. Diameter of cell 12–24 μ. Both valves of resting spores armed with unbranched spines. In addition, primary valve has a crown of thin, parallel needles on the margin.

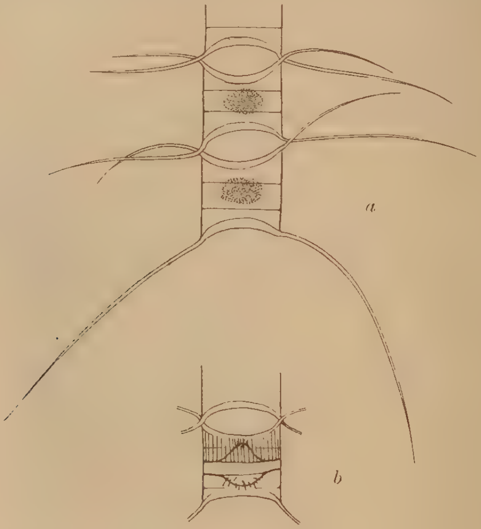

Fig. 63.—*Chaetoceros seiracanthus*. *a.* End of chain. Diameter of cells 17 μ. *b.* Resting spores.

Species 14. **Chaetoceros subsecundus** (Grunow) Hustedt
(65, 1927, p. 709).

Synonyms:

Syndendrium diadema Ehrenberg (37, 1854, pl. 34A, f. 18), *Chaetoceros distans* var. *subsecunda* Grunow (119, 1880, pl. 82, B/f. 6), *Chaetoceros paradoxus* var. *lüdersii* Engler (38, 1883, p. 11), *Chaetoceros paradoxus* var. *subsecunda* van Heurck (119, 1880, p. 20), *Chaetoceros curvisetus* Cleve (24, 1894, p. 12), *Chaetoceros paradoxus* Schütt (107, 1895, p. 37), *Chaetoceros clevei* Schütt (107, 1895, p. 40), *Chaetoceros ralfsii* Schütt (107, 1896, p. 53), *Chaetoceros groenlandicus* Cleve (24, 1896*a*, p. 7), *Chaetoceros groenlandicus* var. *leptopus* Cleve (24, 1896*a*, f. 5), *Chaetoceros diadema* Gran (47, 1897*a*, p. 20), *Chaetoceros paradoxus* Péragallo (97, 1897, pl. 132, f. 1).

Cells rectangular in girdle view with weakly rounded corners. Valves flat to slightly convex in centre. Apertures long, oval, narrowing toward middle. Setae originate at cell corners and are directed transversely to chain axis. Terminal setae acutely divergent. One chromatophore per cell. Diameter of cell 12–44 μ. Primary valve of resting spore armed with 4–12 dichotomously branching spines. Secondary valve smooth.

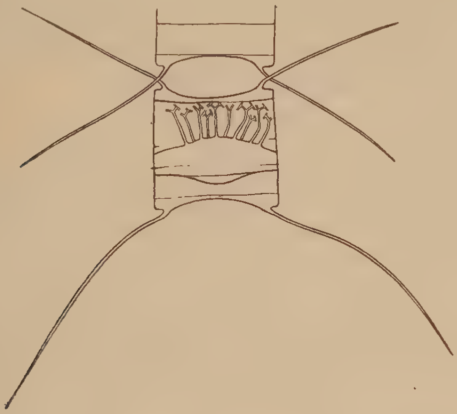

Fig. 64.—*Chaetoceros subsecundus.* Resting spore.

Species 15. **Chaetoceros difficile** Cleve
(24, 1900*a*, p. 20).

Chain straight, loose, 7–15 μ broad. Cell wall weakly siliceous. Valves flat, with no constriction between valve mantle and girdle zone. Sctae very thin, arising at cell corners, with short basal part directed diagonally outward. Apertures wide, hexagonal to rectangular. Chromatophores one per cell attached to broad side of girdle.

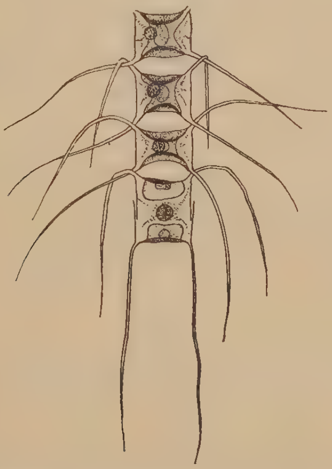

Fig. 65.—*Chaetoceros difficile.* Chain with cell contents. Partly after Karsten, 1905.

Neritic. Reported from Capetown by Karsten as "*Ch.* (*difficile* Cl.?) or a new species". From his short description and figures this would appear to be *Chaetoceros difficile.*

Sec. 10. DIVERSA.

Species 16. **Chaetoceros messanensis** Castracane
(23, 1875, p. 32).

Synonyms:

Chaetoceros spec. Lauder (71, 1864, pl. 3, f. 8), *Chaetoceros furca* Cleve (24, 1897*a*, pl. 1, f. 10), *Chaetoceros furca* var. *macroceros* Schröder (104, 1906*a*, p. 351), *Chaetoceros cornutus* Leudeger-Fortmorel (75, 1898, p. 8).

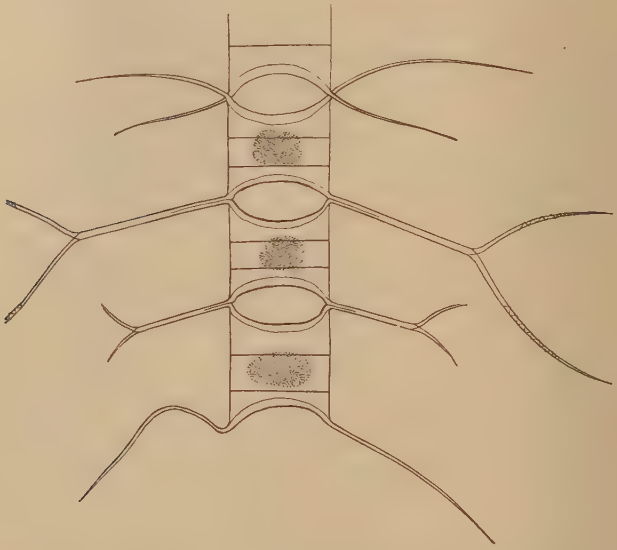

FIG. 66.—*Chaetoceros messanensis.* Diameter of cell 13 μ.

Cells rectangular, corners of adjacent cells touching one another. Diameter of cell 12–14 μ. Chains straight. Valves elliptical. Setae thin. Terminal setae unlike one another, diverging strongly. Some of the inner setae are fused for about two-thirds of their length and then fork. The forked setae are thicker than the others, and armed with spirals of conspicuous small spines. One chromatophore per cell.

Sec. 12. CURVISETA.

Species 17. **Chaetoceros curvisetus** Cleve
(24, 1889, p. 55).

Synonyms:

Chaetoceros spec. Schütt (107, 1889, pl. 14, fs. 1–7), *Chaetoceros secundus* Schütt (107, 1893, p. 25).

Cells rectangular in broad girdle view, with conspicuous corners, elliptical in valve view, apical axis 10–30 μ. Valve mantle low with high corners to apical axis. Chains spirally curved, no distinct terminal cell. Apertures rhombo-elliptical to circular. Setae originate at cell corners and all bend toward outside of curved axis of spiral. Chromatophores large, one per cell, with central pyrenoid.

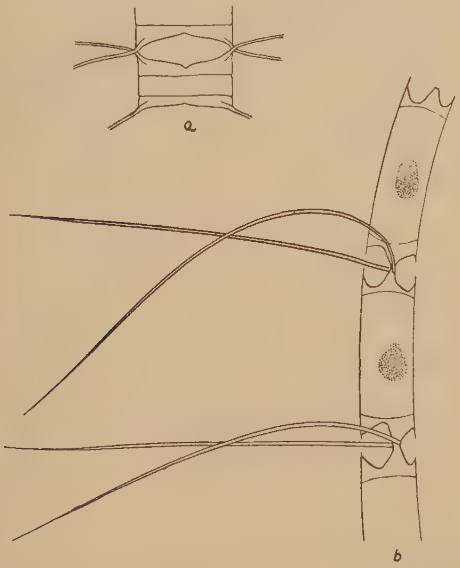

FIG. 67.—*Chaetoceros curvisetus.* *a.* Broad girdle view. *b.* Narrow girdle view.

Sec. 15. SOCIALA.

Species 18. **Chaetoceros socialis** Lauder
(71, 1864, p. 77).

Synonyms:

Chaetoceros wighami Grunow (25, 1880, pl. 7, f. 134), *Chaetoceros lonrezianus* var. *parvula* Grunow (25, 1880, pl. 7, f. 138), *Chaetoceros socialis* var.

solitaria Meunier (84, 1913, p. 46), *Chaetoceros socialis* var. *flabelliformis* Meunier (84, 1913, f. 26), *Chaetoceros socialis* var. *congesta* Meunier (84, 1913).

Cells four-cornered in broad girdle view, corners not touching those of adjacent cell. Width of cell 4·5–15 μ. United into short chains which combine to form colonies. Setae hair-like, originating at cell corners, three short, fourth very long and entwining with long setae of adjacent cells to form colonies. Chromatophores one per cell.

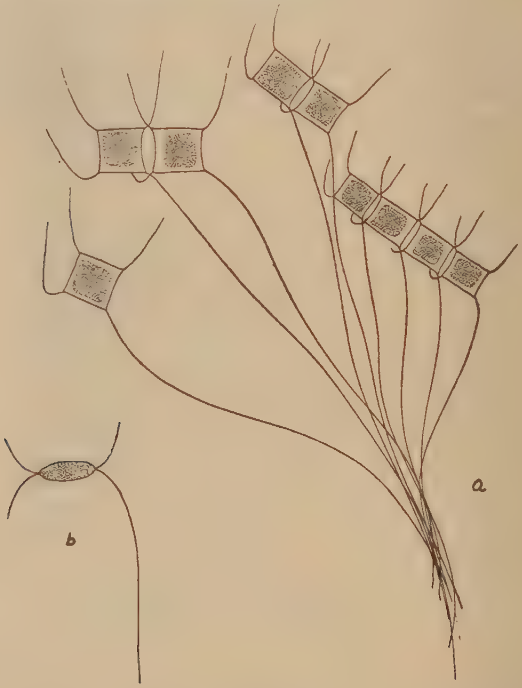

Fig. 68.—*Chaetoceros socialis*. *a*. Part of colony. *b*. Cell in valve view.

Sec. 16. Simplicia.

Species 19. **Chaetoceros gracilis** Schütt (107, 1895, p. 42).

Synonyms:

Eucampia payeri Grunow (56, 1884, p. 107), *Chaetoceros septentrionalis* Cleve (24, 1896*a*, p. 9).

Cells solitary, rectangular in broad girdle view, with conspicuous corners and flat to concave valves, 6–10 μ broad. Setae originate a little within the corners, curved near origin and later more nearly parallel. Chromatophores two per cell.

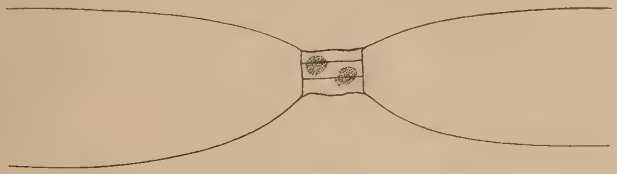

Fig. 69.—*Chaetoceros gracilis.* Apical axis 8·1 μ.

Species 20. **Chaetoceros parallelis** Boden (12, *in press*).

Cells solitary, rectangular in broad girdle view. Valves concave, elliptical in valve view. Valve mantle fairly high, with slight constriction

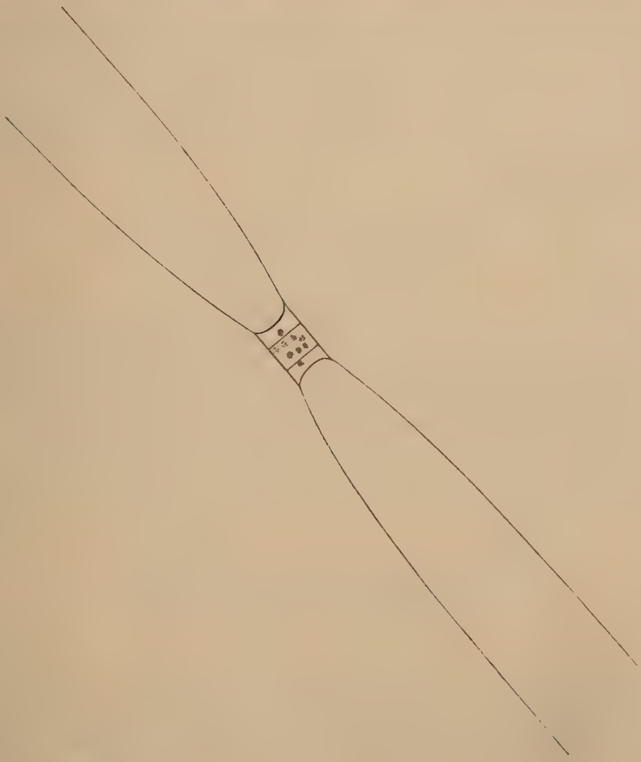

Fig. 70.—*Chaetoceros parallelis.* Diameter of cell 12·1 μ.

at junction of valve mantle and girdle zone. Slender setae originate at cell corners and run almost parallel with pervalvar axis, slightly convex on outside. Chromatophores numerous cocciform bodies. Width of cell in girdle view 10·8–13·5 μ, length of cell 21·6–28 μ, length of setae 121–135 μ.

The numerous chromatophores of this form make it doubtful whether it belongs in this section.

5. BIDDULPHIAE Schütt.
a. Eucampiinae Schütt.
Genera: I. *Eucampia*.
II. *Climacodium*.
III. *Streptotheca*.

Genus I. **EUCAMPIA** Ehrenberg
(37, 1839, p. 151).

Cells united in spiral chains. Valves elliptical in surface view, with two blunt processes but lacking spines or bristles. Intercalary bands difficult to see. Apertures large. Chromatophores numerous, small.

Species: *E. zoodiacus*.
E. cornuta.

Species 1. **Eucampia zoodiacus** Ehrenberg
(37, 1839, p. 151).

Synonyms:

Eucampia britannica W. Smith (113, 1853, p. 25), *Eucampia nodosa* A. Schmidt (103, 1875, pl. 141, f. 28), *Eucampia zoodiacus* var. *cornigera* Grunow (119, 1880, pl. 95B, f. 4), *Eucampia virginica* Grunow (119, 1880, pl. 95B, f. 6), *Eucampia cornuta* var. ? Cleve (24, 1901*a*, p. 326).

Cells flattened, united in spiral chains by two blunt, valvar processes. Apertures variable. Chromatophores small, numerous. Length along apical axis 10–61 μ.

Species 2. **Eucampia cornuta** (Cleve) Grunow
(119, 1880, pl. 95B, f. 5).

Synonym: *Moelleria cornuta* Cleve (24, 1873*a*, p. 7).

Chain and general appearance similar to Eucampia zoodiacus. Valvar processes longer, thinner. Apertures wider. Intercalary bands more prominent. Sculpturing of valves more noticeable and definite in arrangement.

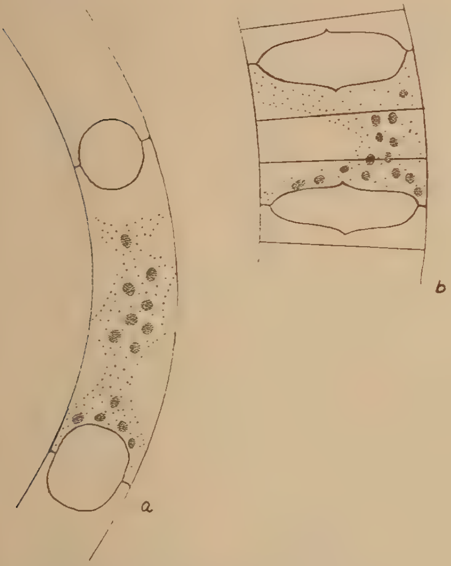

FIG. 71.—*Eucampia zoodiacus.* *a.* Width of chain 22 μ. *b.* Width of chain 39·7 μ.

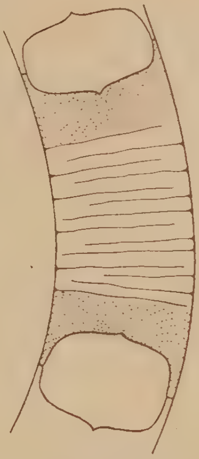

FIG. 72.—*Eucampia cornuta.* Width of cell 13·5 μ. Length of cell 23 μ.

Genus II. **CLIMACODIUM** Grunow

(56, 1868, p. 102).

Chains straight with apertures oval or oblong. Hammer-like ends of cells touch to form chains. Cell walls weakly siliceous. Chromatophores numerous, small.

Species: *C. frauenfeldianum.*

Species 1. **Climacodium frauenfeldianum** Grunow

(56, 1868, p. 102).

Synonyms:

Climacodium (*frauenfeldianum* var. ?) *jacobi* Cleve (24, 1897*a*, p. 22), *Climacodium atlanticum* Mangin (81, 1910, p. 383).

Chains ribbon-like with large rectangular apertures. Pervalvar axis 10–15 μ. Intercalary bands absent. Chromatophores small, numerous.

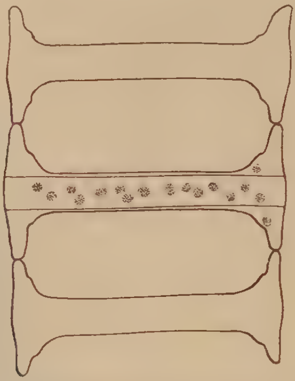

FIG. 73.—*Climacodium frauenfeldianum.* Width of cell 175·5 μ, length 12 μ.

Genus III. **STREPTOTHECA** Shrubsole
(110, 1890, p. 259).

Cells square, flat, forming ribbon-like chains. United by valve faces leaving hardly any aperture. Chains twisted. Cell wall weakly siliceous. Chromatophores numerous, small. Valve surfaces armed with rudimentary central knob.

Species: *S. thamesis.*

Species 1. **Streptotheca thamesis** Shrubsole
(110, 1890, p. 259).

Cells square, flat, twisted through 90°. Valves with two deeply placed knobs, fitting into corresponding depressions on valve surface of adjacent cell. Chromatophores numerous, small rounded plates. Width of cell 60–160 μ.

b. Triceratiinae Schütt.
Genus: I. *Ditylum.*

Genus I. **DITYLUM** Bailey
(8, 1862, p. 352).

Valve three- to four-cornered, with a strong, siliceous, hollow central spine, and a ribbed marginal ridge. Cells elongated, prismatic to cylindrical, usually solitary. Cell walls weakly siliceous. Chromatophores numerous, small.

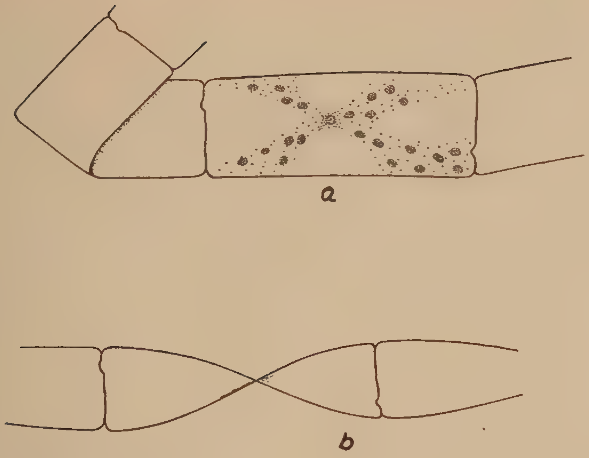

FIG. 74.—*Streptotheca thamesis.* *a.* Part of chain, width 62 μ. *b.* Typical twisting.

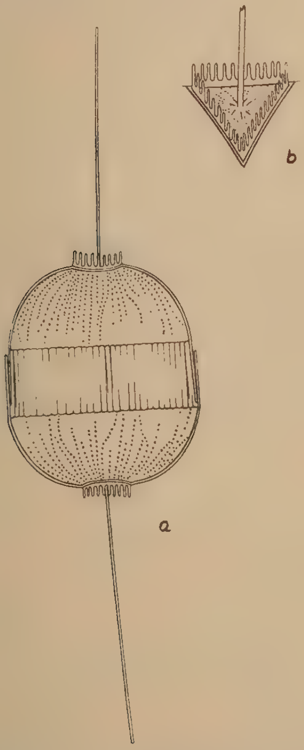

FIG. 75.—*Ditylum brightwellii.* *a.* Diameter of cell 67 μ. *b.* Ridge on valve.

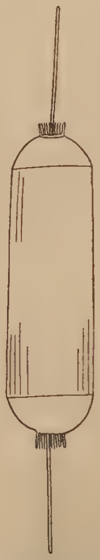

FIG. 76.—*Ditylum brightwellii.* Diameter of cell 35 μ.

Species: *D. brightwellii.*

Species 1. **Ditylum brightwellii** (West) Grunow
(119, 1880, pl. 114, fs. 3–9).

Synonyms:

Triceratium undulatum Brightwell (18, 1858, p. 154), *Triceratium brightwellii* West (121, 1860, p. 149), *Ditylum trigonum* Bailey (8, 1862, p. 332), *Ditylum inaequale* Bailey (8, 1862, pl. 7, fs. 12–14), *Ditylum brightwellii* var. *inaequalis* Grunow (119, 1880, pl. 114, f. 3), *Ditylum brightwellii* var. *trigona* Grunow (119, 1880, pl. 114, f. 9), *Ditylum undulatum* Mann (82, 1907, p. 297).

Cells prism-shaped with strongly rounded angles, to nearly cylindrical. Diameter of cell 25–100 μ. Valves triangular with central hollow spine. Areolae in radial rows on valve surface, in pervalvar rows on valve mantle. Intercalary bands scale-like. Cell wall weakly siliceous. Chromatophores small, numerous.

c. Biddulphiinae Schütt.
Genus: I. *Biddulphia.*

Genus I. **BIDDULPHIA** Gray
(51, 1821, p. 294).

Cells single or in chains, box-shaped to cylindrical. Cell wall strongly siliceous. Valves elliptical to triangular or quadrangular. Strongly developed horns or processes on valves at corners or ends of ellipse. Fine slime pores present at ends of processes. Through these pores appear slime cushions which hold the cells together in chains. In planktonic forms the valves are usually armed with spines. The girdle zone is sharply differentiated from the valve zone, prism-shaped to cylindrical, cross-striated, with indistinct intercalary bands. Chromatophores numerous, small, lying against the cell wall.

Species: *B. mobiliensis.*
B. regia.
B. longicruris.

Species 1. **Biddulphia mobiliensis** Bailey
(7, 1845, p. 336).

Synonyms:

Zygoceros (*Denticella* ?) *mobiliensis* Bailey (7, 1851, p. 40), *Biddulphia baileyi* W. Smith (113, 1853, pl. 45, f. 322*b*), *Denticella mobiliensis* Grunow (56, 1884, p. 7), *Odontella mobiliensis* Grunow (56, 1884, p. 58).

Cells single, sometimes united in short chains by valvar spines. Cell walls relatively thin, weakly siliceous. Valves elliptical, convex, with flat central portion. Valve processes slender, directed diagonally outward. Two long spines directed obliquely outward. The spines are about as far from each other as they are from the valve processes. Sculpturing very fine. Length of apical axis 45–160 μ.

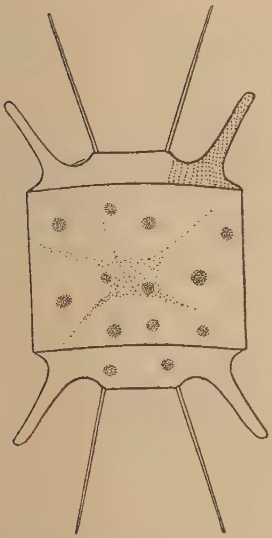

FIG. 77.—*Biddulphia mobiliensis.* Apical axis 94 μ.

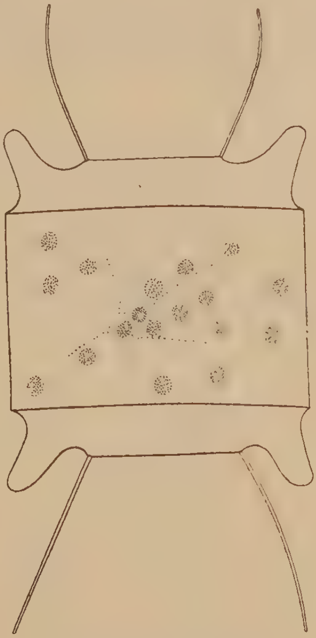

FIG. 78.—*Biddulphia regia.* Apical axis 170 μ.

Species 2. **Biddulphia regia** (Schultze) Ostenfeld (93, 1908*b*, p. 7).

Synonyms:

Denticella regia Schultze (105, 1858, p. 21), *Biddulphia baileyi* W. Smith (113, 1853, pl. 62, f. 322*d*).

Cells similar to, and frequently confused with, *B. mobiliensis.* Central part of valve wider than depressions. Spines further from each other and nearer to processes than *B. mobiliensis.* Processes blunter than *B. mobiliensis.* Length of apical axis 60–180 μ.

Species 3. **Biddulphia longicruris** Greville (53, 1859, p. 163).

Cells usually in straight chains. Valves elliptical, with a conical protuberance in centre bearing usually two (sometimes three) long spines. Spines usually bent to run more or less parallel with pervalvar axis, capitate-truncate. Valvar processes longer than wide. Valve mantle usually indented above junction with girdle zone. Valves and girdle zone finely punctated. Chromatophores small, numerous, near cell wall. Length of apical axis 15–110 μ.

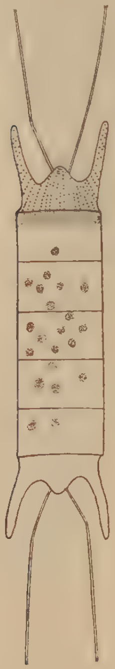

Fig. 79.—*Biddulphia longicruris.* Apical axis 94·5 μ.

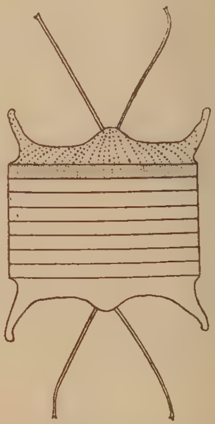

Fig. 80.—*Biddulphia longicruris* var. "*hyalina.*" Apical axis 160 μ.

Variety "**hyalina**" (Schröder) Cupp (30, 1943, p. 157).

Synonyms:

Biddulphia hyalina Schröder (104, 1906*a*, p. 353), *Biddulphia extensa* Mann (82, 1907, p. 302), *Biddulphia longicruris* Greville (48, 1931, p. 491).

Shape of valve similar to type. Spines shorter. Valvar processes shorter, blunter. Intercalary bands usually lacking. Chromatophores numerous, small. Length of apical axis 24–184 μ.

d. Hemiaulinae Schütt.
Genus: I. *Hemiaulus.*

Genus I. **HEMIAULUS** Ehrenberg
(37, 1844, p. 199).

Cells solitary or in chains. Valves elliptical in section, with two processes at ends of apical axis parallel with pervalvar axis. These processes are armed with one or more hyaline claws at the end. Cell wall strongly or weakly siliceous, punctated. Chromatophores numerous.

Species: *H. hauckii.*

Species 1. **Hemiaulus hauckii** Grunow
(119, 1880, pl. 103, f. 10).

Synonym: *Hemiaulus delicatulus* Lemmerman (74, 1905, p. 647).

Cells rectangular in broad girdle view with long, thin, pointed processes uniting them into chains. Apical axis 8–75 μ. Cells long, straight or twisted. Valve surface flat to slightly concave. Apertures large. Cell wall weakly siliceous.

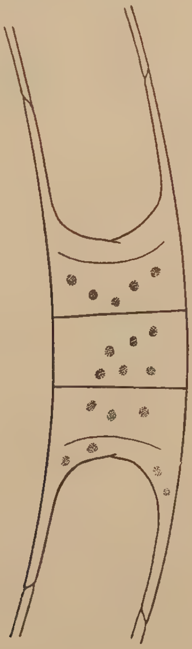

Fig. 81.—*Hemiaulus hauckii.* Apical axis 32 μ.

6. Euodieae Schütt.
Genus: I. *Hemidiscus.*

Genus I. **HEMIDISCUS** Wallich (120, 1860, p. 42).

Cells cuneiform. Valves semicircular to asymmetrically elliptical. Valves flat with short valve mantles. Cell wall weakly or strongly siliceous, with regular, thick areolation. Marginal spinulae often present, also an "eye" near middle of ventral valve margin. Chromatophores numerous, small bodies.

Species: *H. cuneiformis.*

Species 1. **Hemidiscus cuneiformis** Wallich (120, 1860, p. 42).

Synonyms:

Dichomeris subtilis Ehrenberg (37, 1861, p. 294), *Euodia inornata* Castracane (23, 1866, p. 149), *Euodia radiata* Castracane (23, 1886, p. 149), *Euodia cuneiformis* Schütt (107, 1896, p. 100), *Euodia gibba*, auct. nonnul., nec Bailey.

Cells cuneiform, solitary. Valves almost semicircular; dorsal margin strongly convex, ventral margin weakly so, often furnished with a median inflation on the ventral side. Valve finely areolated in irregular radial fascicules. No central hyaline area or rosette. Small papillae on apices. Row of small spinulae on ventral margin with small "eye" half-way along. Girdle simple, no intercalary bands. Apical axis 80–174 μ, transapical axis 44–90 μ. Chromatophores numerous, small rounded bodies.

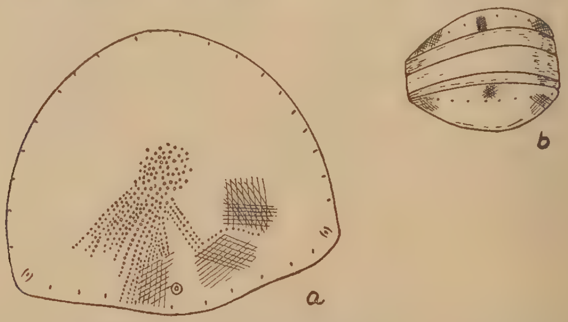

Fig. 82.—*Hemidiscus cuneiformis.* *a.* Valve view. *b.* Girdle view. After Cupp, 1943.

Oceanic. Reported by Hendy, who found the great number of species and varieties which have been established rely on variable characteristics, and whose specimens formed a "series of intermediate forms that made it impossible to recognise the value of the nomenclatural species and varieties".

CLASSIFICATION OF THE PENNATAE.

- B. **PENNATAE** Schütt.
  - B_1. *Araphideae.*
    - IV. **Fragilarioideae** Schütt.
      - 7. Tabellaireae Schütt.
        - *a.* Licmophorinae Hustedt.
      - 8. Fragilarieae Schütt.
        - *a.* Diatominae Schütt.
        - *b.* Fragilariinae Schütt.
  - B_2. *Monoraphideae.*
    - V. **Acnanthoideae** Schütt.
      - 9. Cocconeideae Schütt.
      - 10. Acnantheae Schütt.
  - B_3. *Biraphideae.*
    - VI. **Naviculoideae** Schütt.
      - 11. Naviculeae Schütt.
    - VII. **Nitzschioideae** Schütt.
      - 12. Nitzschieae Schütt.
    - VIII. **Surirelloideae** Schütt.
      - 13. Surirelleae Schütt.

KEY TO THE PENNATAE.*

B. Valves not centrally constructed, not arranged in relation to a central point but to a median line. Bilaterally symmetrical. Outline generally boat-shaped or rod-shaped, sometimes oval, cuneate, crescent-shaped, or sigmoid; markings generally pinnate or transverse. True raphe, or hyaline median line (pseudoraphe), or raphe obscured by lateral wings or keel (cryptoraphe) always present. Processes such as horns, spines, etc., uncommon. Cell capable of spontaneous movement if a true raphe is present. Auxospore formation sexual or reduced. Microspores not certainly found . . . Section **PENNATAE.**

B_1. Raphe absent. Pseudoraphe usually present . . Subsection **Araphideae.**

IV. Cells in general rod-shaped to tabular-prism-shaped, in valve view usually more or less linear, seldom club-shaped. In girdle view linear to tabular-rectangular. Intercalary bands and septa frequently present. Valves with transapical striae or ribs, sometimes areolated-punctated, often with mucilage pores. Without a true raphe, but usually with a median pseudoraphe. Chromatophores usually more or less numerous small platelets, seldom a single large plate. Auxospore formation, so far as known, asexual . . . Subfamily **Fragilarioideae.**

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* Altered from Cupp (1943, p. 36) to fit the Pennate genera of this region.

7. Cells in valve view usually linear, more seldom wedge-shaped, frequently with transapical inflations or constrictions. In girdle view usually linear to tabular, seldom wedge-shaped. Intercalary bands and septa always present and distinct. Valvar plane not bent in the pervalvar direction, the two valves of a cell usually entirely alike. Cells usually united into bands. Marine and freshwater forms . . . . . Tribe **Tabellarieae.**

    (*a*) Cells with poles of apical axis unlike. In girdle view, wedge-shaped. Intercalary bands and septa present. Cells stalked and often united into strongly branched colonies. Marine . . . Subtribe **Licmophorinae.**

    Genus: *Licmophora.*

8. Cells usually rod-shaped. Usually linear in both valve and girdle view, seldom wedge-shaped or with tabular girdle view. Intercalary bands sometimes present, but always without or with only very rudimentary septa . . . Tribe **Fragilarieae.**

    (*a*) Valves with transapical ribs that are, however, sometimes limited to one valve of a cell or to one single middle rib. Freshwater or marine forms. Cells as a rule united into closed or zigzag bands . . Subtribe **Diatominae.**

    Genus: *Plagiogramma.*

(*b*) Valves without special transapical ribs, or the entire membrane provided with a supporting framework of stronger or weaker ribs. Freshwater and marine forms. Cells solitary or united into colonies of various forms . . Subtribe **Fragilariinae.**

Genera:
Fragilaria.
Thalassionema.
Thalassiothrix.
Asterionella.

B$_2$. One valve of the cell always with Navicula-like raphe, the other without or with a rudimentary raphe-knot . . . . Subsection **Monoraphideae.**

V. Cells with linear, lanceolate, or elliptical valvar plane, more or less distinctly bent about the apical or transapical axis. Intercalary bands and septa absent; valves, however, sometimes with polar pseudosepta, individual species also with an intercalary ring with rudimentary chamber-formation on the valve margin similar to the septa-chambers in the genus *Mastogloia*. Structure of the membrane: transapical rows of more or less delicate poroids, often in quincunx. The membrane lying between the transapical rows stronger, often thickened, rib-like. The two valves of a cell often considerably differentiated in regard to the structure as well as to the development of the raphe Subfamily **Acnanthoideae.**

9. Valves isobilateral upon both apical and transapical axes . Tribe **Cocconeideae.**

Genus: *Cocconeis.*

10. Cells bent about the transapical axis, sometimes also about the apical axis; the valve with the raphe, concave; the one without a raphe, convex. One valve always with a developed raphe, the other without, seldom with a very short raphe-knot or with a rudimentary raphe. Outline of valve linear-lanceolate, seldom elliptical. Intercalary bands sometimes present, true septa absent . Tribe **Acnantheae.**

Genus: *Acnanthes.*

B_3. Both valves with developed raphe . . . . . Subsection **Biraphideae.**

VI. Cells of various types as regards structure of membrane, cell contents, and general form. All forms with a similar characteristic raphe system: an outer and inner fissure and accompanying end and central knots. Knots often greatly reduced or in many species only slightly developed. Inner and outer fissure often difficult to distinguish from each other. Raphe usually in the valvar plane, generally distinct, not developed as a canal-raphe; usually without a keel or strongly developed wings, but when present always without marginal canal and keel puncta . . . . Subfamily **Naviculoideae.**

11. Cells as a rule of symmetrical construction, transapical axis only seldom with unlike ends. In girdle view usually rectangular, valves elliptical, linear or lanceolate, often **S**-shaped, seldom club-shaped or crescent-shaped. Raphe usually in the valvar plane. Not perceptibly keeled. Keels if present not punctate. Intercalary bands and septa sometimes present, usually absent. Cells usually solitary, sometimes in gelatinous tubes or on a gelatinous stalk, seldom united into bands and then often difficult to distinguish from *Fragilaria* . Tribe **Naviculeae.**

Genus: *Pleurosigma.*

VII. Keel with canal-raphe lying in the valvar plane, often displaced transapically as far as to the valve margin. In this latter case only one margin of each valve with a keel. Both valves with canal-raphe. Keel with puncta . . . Subfamily **Nitzschioideae.**

12. Raphe obscured by punctate marginal keel. Markings always transverse . . . . Tribe **Nitzscheae.**

Genus: *Nitzschia.*

VIII. Keel with canal-raphe lying on the valve margin and running around the entire valve. Raphe system consequently apparently doubled. Raphe hidden in lateral winged keel . . . . Subfamily **Surirelloideae.**

13. As above . . . . . Tribe **Surirelleae.**

Genus: *Campylodiscus.*

SYSTEMATIC ACCOUNT OF THE PENNATAE.

B. **PENNATAE.**

IV. **Fragilarioideae.**

7. Tabellarieae.

a. Licmophorinae Hustedt.
Genus: I. *Licmophora.*

Genus I. **LICMOPHORA** Agardh
(1, 1830, p. 628).

Cells wedge-shaped in girdle view, frequently attached by mucous stalks to living plankton, *e.g.* copepods, or suspended organic matter. Valves wedge- or club-shaped, cross-striated, pseudoraphe distinct. Intercalary bands present with a penetrating septum on upper end. Chromatophores few to numerous, large to small.

Species: *L. ehrenbergii.*
L. lyngbyei.

Species 1. **Licmophora ehrenbergii** (Kützing) Grunow
(56, 1867, p. 36).

Synonyms:

Podosphenia ehrenbergii Kützing (70, 1844, p. 121), *Podosphenia cuneata* Ehrenberg (37, 1838, pl. 17, f. 8).

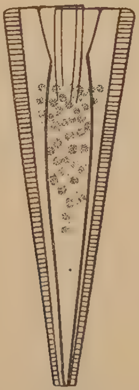

Fig. 83.—*Licmophora ehrenbergii.* Cell in girdle view, length 86·4 μ, width 24·3 μ, striae 9 in 10 μ.

Cells in girdle view wedge-shaped with rounded upper corners. In valve view superior apex rather acute, pseudoraphe broad and distinct, strong clear striations 8–11 in 10 μ. Length of cell 60–180 μ, width 15–30 μ. Chromatophores granular.

Species 2. **Licmophora lyngbyei** (Kützing) Grunow
(56, 1867, p. 35).

Synonym: *Podosphenia lyngbyei* Kützing (70, 1844, p. 121).

Cells united in colonies by means of dichotomously branching mucous stipes. Cells in girdle view three-cornered with both upper corners rounded, clavate in valve view with broad end rounded. Valves flat, transversely striated (10–16 striae in 10 μ), and furnished with a prominent pseudoraphe. Connective zone cuneate, septate. Chromatophores numerous, cocciform bodies. Length of valve 54–80 μ.

Neritic and littoral, frequently epiphytic and epizootic. Reported from this area by Karsten.

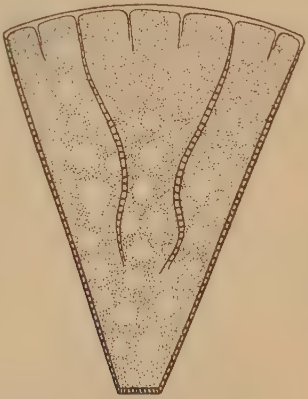

Fig. 84.—*Licmophora lyngbyei.* After Wilson in Lebour, 1930.

8. Fragilarieae Schütt.

a. Diatominae Schütt.

Genus: I. *Plagiogramma.*

Genus I. **PLAGIOGRAMMA** Greville
(53, 1859*c*, p. 207).

Cells more or less rectangular in girdle view, lacking intercalary bands or septa. Valves linear-lanceolate, with transapical ribs forming pseudosepta. Sometimes two pairs of ribs present, one near centre of valve and one near end; sometimes several pairs of ribs present; sometimes only one rib in centre. Cell wall with delicate transapical and longitudinal ribs. Puncta and areolae in regular longitudinal rows. Cells form close chains.

Species: *P. vanheurckii.*

Species 1. **Plagiogramma vanheurckii** Grunow (119, 1880, p. 145).

Cells rectangular in girdle view, but constricted below the poles, forming a lanceolate middle part with knob-like corners. Valves lanceolate, 15–45 μ long, 4–5 μ broad. Valve centre has single deeply penetrating pseudoseptum. Transapical and longitudinal striations 12–16 in 10 μ.

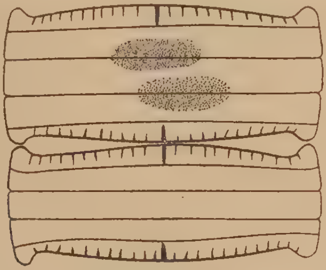

FIG. 85.—*Plagiogramma vanheurckii.* Length of cell 27 μ.

b. Fragilariinae Schütt.

Genera: I. *Fragilaria.*
II. *Thalassionema.*
III. *Thalassiothrix.*
IV. *Asterionella.*

Genus I. **FRAGILARIA** Lyngbye (80, 1819, p. 182).

Cells in girdle view rectangular and rod-like. United by whole valve surface into ribbon-like chains. Valves linear to elliptical-lanceolate or enlarged or constricted in centre. Valves flat, transapically striated, bilaterally symmetrical, lacking or with rudimentary pseudoraphe, lacking raphe.

Species: *F. granulata.*
F. karstenii.

Species 1. **Fragilaria granulata** Karsten
(68, 1907, p. 396).

Cells united by valve surfaces to form short, curved chains. Valves linear-lanceolate, transversely striated. Length 40–56 μ. Chromatophores numerous, rounded granules.

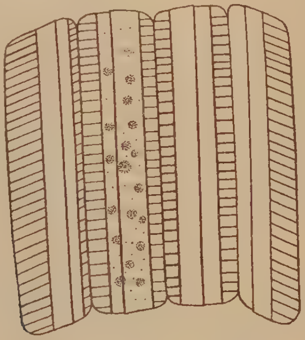

Fig. 86.—*Fragilaria granulata.* Length of cell 48·6 μ.

Species 2. **Fragilaria karstenii** Boden, nom. nov.

Synonym: *Fragilaria capensis* Karsten (68, 1905, p. 173).

42 μ. Valve form? Cells in long bands, valve to valve, rendering it difficult to obtain a valve view. In girdle view one distinguishes 12 to 14 transverse striae on the valve margin. Chromatophores here number four.

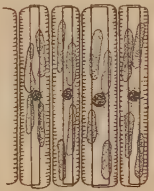

Fig. 87.—*Fragilaria karstenii.* Four cells in girdle view showing cell contents. After Karsten, 1905.

The new name given above is necessary because *Fragilaria capensis* is preoccupied (*F. capensis* Grunow, 1863, p. 143). In the Mill's Index (74, 1933, p. 725) *F. capensis* Karsten is indicated as a synonym for *F. capensis* Grunow. The above description is Karsten's. This form differs from *F. capensis* Grunow in that the cells are united in long bands, the cells are 42 μ long, and the transverse striae are only 3 in 10 μ. *F. capensis*

Grunow is diagnosed by its extremely short bands, by its cells being only 15 to 25 μ long and having 14 to 16 striae in 10 μ. The two forms are therefore different and Karsten's term constitutes a primary homonym and must be replaced. The diagram given by Karsten is reproduced here although it does not agree in all respects with his description.

Genus II. **THALASSIONEMA** Grunow ex Hustedt (65, 1927, p. 244).

Cells linear in girdle view. Valves linear to lanceolate, united by gelatinous cushion at one end into zigzag or star-shaped colonies. Intercalary bands and septa lacking. Numerous, regularly spaced, small spines on valve margins. Chromatophores numerous, small granules. The authority for this genus is attributed to Hustedt by Hendy (1937).

Species: *T. nitzschioides.*

Species 1. **Thalassionema nitzschioides** Hustedt (65, 1932, p. 244).

Synonyms:

Synedra nitzschioides Grunow (56, 1862, p. 403), *Thalassiothrix nitzschioides* Grunow (119, 1880, pl. 43, fs. 7–10), *Thalassiothrix curvata*

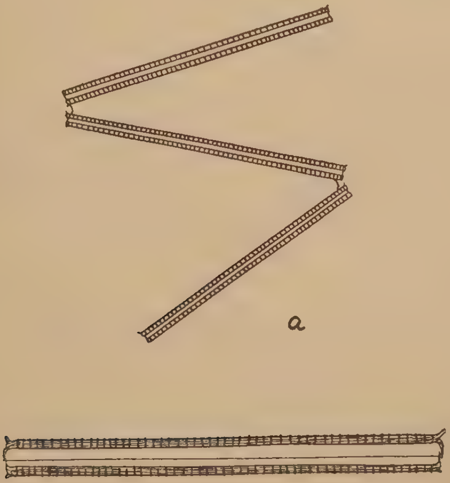

FIG. 88.—*Thalassionema nitzschioides.* *a.* Zigzag colony. *b.* Cell in girdle view, length 48·6 μ, width 3·8 μ.

Castracane (23, 1880, p. 55), *Thalassiothrix frauenfeldii* Cleve (24, 1894, p. 6), *Thalassiothrix frauenfeldii* var. *nitzschioides* Jørgensen (67, 1900, p. 21).

Cells linear in girdle view, narrow. Valves narrow, linear with bluntly rounded ends, 30–110 μ long, 2–4 μ broad. Marginal spines small, 10–12 in 10 μ. Colonies zigzag or star-shaped.

Genus III. **THALASSIOTHRIX** Cleve and Grunow
(25, 1880, p. 108).

Cells narrow, linear in girdle view, solitary or forming zigzag or star-shaped colonies. Valves linear to slightly lanceolate, ends dissimilar. Intercalary bands and septa lacking. Valve margins often armed with small spines. Chromatophores numerous, small granules.

Species: *T. longissima.*

Species 1. **Thalassiothrix longissima** Cleve and Grunow
(25, 1880, p. 108).

Synonym: *Synedra thalassiothrix* Cleve (24, 1873*b*, p. 22.)

Cells solitary, thread-like, curved. Valves narrow linear, one end more narrowed than other. Length 1–4 mm., width 3–4 μ. Valve margin armed with delicate spines, about 3 in 10 μ in centre, fewer or lacking at ends.

Genus IV. **ASTERIONELLA** Hassal
(59, 1855, p. 10).

Cells rod-like with distinctly dissimilar ends, united by larger end into star-shaped, spirally curved, or straight colonies. Valves linear with enlarged area near one or both ends, striated, with narrow pseudoraphe. Intercalary bands and septa lacking.

Species: *A. japonica.*

Species 1. **Asterionella japonica** Cleve and Möller
(27, 1878, No. 307).

Synonyms:

Asterionella glacialis Castracane (23, 1886, p. 50), *Asterionella spathulifera* Cleve (24, 1897*c*, p. 101).

Cells in star-like spiral colonies. In girdle view narrow, linear, with one end enlarged. Length of valve 50–100 μ. Transapical striae 34 in 10 μ. Chromatophores 1 or 2 small plates confined to enlarged end.

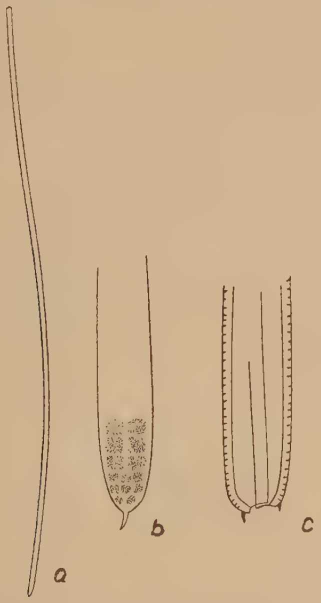

FIG. 89.—*Thalassiothrix longissima*. *a*. Entire cell, length 1 mm. *b*. End of cell, valve view. *c*. End of cell, girdle view.

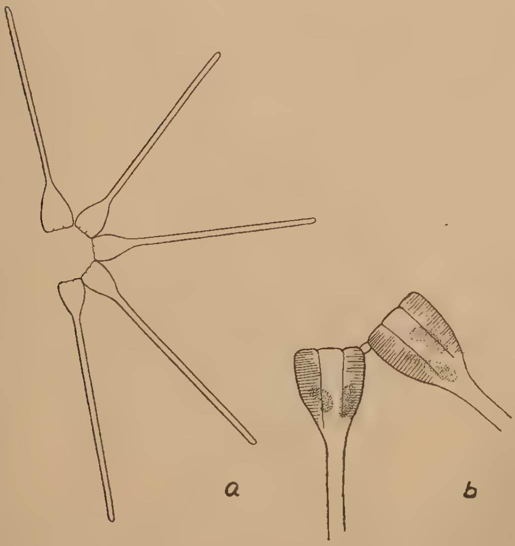

FIG. 90.—*Asterionella japonica*. *a*. Part of colony. *b*. Heads of two cells.

V. **Acnanthoideae** Schütt.

9. COCCONEIDEAE Schütt.

Genus: I. *Cocconeis.*

Genus I. **COCCONEIS** Ehrenberg

(37, 1838, p. 193).

Valves broadly elliptical. Upper valve with more or less narrow longitudinal area. Valve punctated in transverse and, frequently, longitudinal rows. Lower valve usually with marginal area. Valves usually bent along longitudinal axis.

Species: *C. costata.*

Species 1. **Cocconeis costata** Gregory

(52, 1855, p. 39).

Synonyms:

Surirella quarnerensis Grunow (56, 1862, p. 456), *Rhaphoneis scutelloides* Grunow (56, 1862, p. 393), *Cocconeis costata* var. *typica* Cleve (24, 1894–95, p. 182).

Elliptical to orbicular. Upper valve with narrow axial area and strong transverse costae alternating with double rows of puncta. Lower valve with narrow axial area, with central area dilated to a fascia. Cells 12–40 μ long, 8–18 μ broad. Radial transapical striae 6–10 in 10 μ.

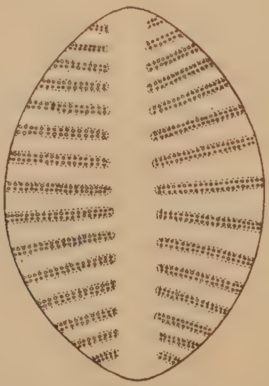

FIG. 91.—*Cocconeis costata.* Upper valve, length 13·5 μ, width 8 μ, striae 10 in 10 μ.

10. Acnantheae Schütt.

Genus: I. *Acnanthes.*

Genus I. ACNANTHES Bory (13, 1822).

Cells solitary or united into ribbon-like chains, with or without a mucous stalk. Valves lanceolate or elliptical. One valve has a raphe and central nodule, the other a pseudoraphe. More or less distinct, transapical striae.

Species: *A. vanhoeffenii.*

Species 1. **Acnanthes vanhoeffenii** Heiden and Kolbe (61, 1928, p. 580).

Valves lanceolate, length 30–46 μ, width 10–12 μ, radiate striae 10 in 10 μ, wider in mid-portion, 8·5 in 10 μ. Both valves have narrow, lanceolate axial area. Central area of upper valve is asymmetrical due to a shortening of the transapical striae of one side. Narrow lanceolate pseudoraphe on lower valve.

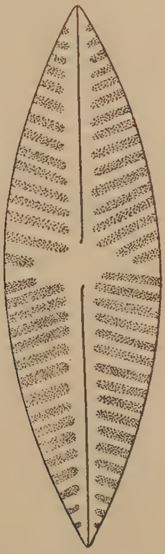

Fig. 92.—*Acnanthes vanhoeffenii.* Upper valve, length 33 μ, width 10·8 μ, striae 10 in 10 μ.

VI. **Naviculoideae** Schütt.

11. NAVICULEAE Schütt.

Genera: I. *Diploneis.*
II. *Pleurosigma.*

Genus I. **DIPLONEIS** Ehrenberg em. Cleve
(24, 1894–95, p. 96).

Valves usually short, ends rounded, constricted or not in middle. Central nodule prolonged into horns or processes enclosing the median line. On both sides of the horns are furrows of varying width. Fine transverse striae or coarser costae continue in rudimentary state across furrows. The transverse costae are either crossed by longitudinal costae, giving the valve a reticulate appearance, or they alternate with rows of fine puncta or alveoli.

Species: *D. smithii.*

Species 1. **Diploneis smithii** (Brébisson) Cleve
(24, 1894–95, p. 96).

Synonyms:

Navicula elliptica W. Smith (113, 1853, p. 48), *Navicula smithii* Brébisson (113, 1853, p. 92), *Pinnularia scutellum* O'Meara (92, 1875, p. 382), *Navicula smithii* var. *borealis* f. *minor* Grunow (56, 1884, pl. 1, f. 41), *Navicula smithii* var. *scutellum* O'Meara (119, 1886, p. 198), *Navicula gyrinida* Mann (82, 1907, p. 344), *Diploneis gyrinida* Mills (85, 1933, p. 618).

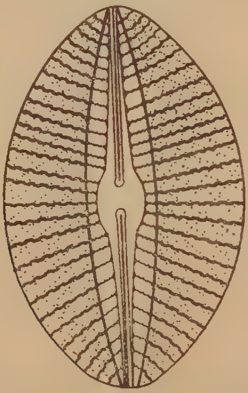

FIG. 93.—*Diploneis smithii.* Length 27 μ, width 15·5μ, striae 12 in 10 μ.

Valve elliptical, 25–200 μ long, 15–75 μ broad. Central nodule small to fairly large. Terminal nodules close to end. Furrows close to horns, of varying width. Transapical striae robust, 5–12 in 10 μ.

Genus II. **PLEUROSIGMA** W. Smith

(113, 1852, p. 1).

Cells elongated, linear to lanceolate, usually sigmoid. Striae punctate, arranged in oblique and transverse or oblique and longitudinal rows. Central area small. Narrow connective zone, cells sometimes twisted or constricted in the middle. Chromatophores usually two bands, one to each valve, with numerous pyrenoids.

Gran (1905) and Lebour (1930) use the generic term "*Gyrosigma*" (Hassal, 1845) as equal to *Pleurosigma*. Cleve (1894), Hustedt (1930), and Cupp (1943) separate *Pleurosigma* and *Gyrosigma* and place in *Pleurosigma* those forms in which the striations in the apical axis are crossed by oblique striations, while *Gyrosigma* designates those forms in which the longitudinal striations cross the transverse striations at right angles. Hendy (1937), considering this did not warrant generic distinction, lumped the two divisions under the title *Pleurosigma* W. Smith, using it in the sense that W. Smith used it in 1852. The one species recorded here belongs to the genus *Pleurosigma* whether the name is used in the restricted or broader sense.

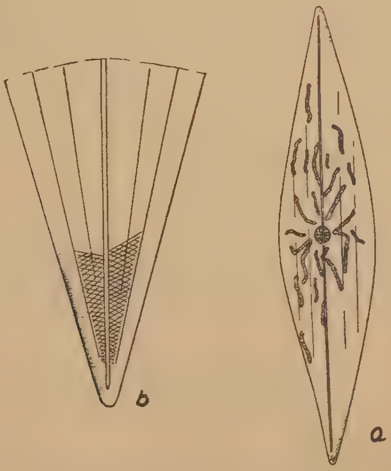

FIG. 94.—*Pleurosigma capense.* *a.* Valve view. *b.* End of cell. After Karsten, 1905.

Species: *P. capense.*

Species 1. **Pleurosigma capense** Karsten
(68, 1905, p. 175).

The valves show the conventional decussate marking in parallel striae running in three different directions, about 20 in 10 μ. Moreover, three of the lines almost parallel with the raphe run on either side of the midline at regular intervals. This is peculiar to this form. Length 320 μ. Chromatophores short bands or rods, radiating from the nucleus in systrophe or arranged on valve surfaces.

Described from here by Karsten.

VII. **Nitzschioideae** Schütt.

12. Nitzschieae Schütt.
Genus: I. *Nitzschia.*

Genus I. **NITZSCHIA** Hassal em. Grunow
(25, 1880, p. 103).

Cells spindle-shaped, single or colonial. Valve keeled, possessing raphe but lacking central nodule. Keels of valves diagonally opposite. Transverse punctate striations. Chromatophores two, band-like.

Species: *N. seriata.*
N. longissima.
N. paradoxa.
N. delicatissima.
N. closterium.

Key to Species.

A. Cells solitary.
  B. Ends hair-like, flexible . . . . . . *N. closterium.*
  C. Ends extended into very long horns . . . . *N. longissima.*

A_1. Cells in chain-like colonies.
  D. Chain straight.
    E. Cells large, 6 μ wide . . . . . . *N. seriata.*
    F. Cells delicate, 2 μ wide . . . . . *N. delicatissima.*
  D_1. Chain variable in form with the movement of the cells within it . . . . *N. paradoxa.*

Species 1. **Nitzschia seriata** Cleve
(24, 1883*a*, p. 478).

Synonyms:

Synedra holsatiae Hensen (63, 1887, p. 91), *Nitzschia fraudulenta* Cleve (24, 1897*b*, p. 300).

Cells spindle-shaped, pointed to rounded ends. United into stiff, hair-like chains by overlapping points of cells. Length of valve 80–140 μ, width 6–8 μ. Striations 14–19 in 10 μ, punctate.

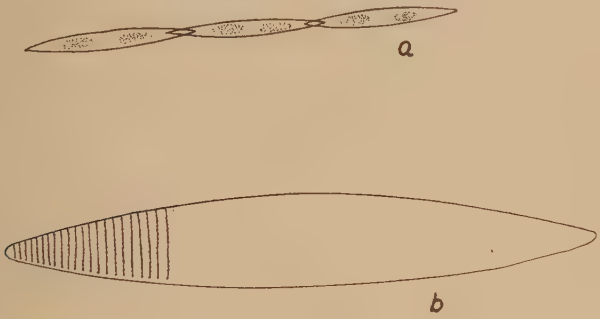

FIG. 95.—*Nitzschia seriata.* *a.* Chain of three cells. *b.* Single cell, valve view. Length 102 μ, width 7 μ, striae 15 in 10 μ.

Species 2. **Nitzschia longissima** (Brébisson) Ralfs
(100, 1861, p. 783).

Synonyms:

Ceratoneis longissima Brébisson (70, 1849, p. 891), *Nitzschia birostrata* W. Smith (113, 1853, p. 42).

Cells solitary. Valves linear-lanceolate, ends extended into long horns. Length 125–250 μ. Chromatophores confined to widened centre. Striations and puncta very difficult to see. About 16 striae in 10 μ.

Species 3. **Nitzschia paradoxa** (Gmelin) Grunow
(119, 1880, p. 176).

Synonym: *Bacillaria paradoxa* Gmelin (77, 1788, p. 3903).

Cells slide along each other, united in movable colonies. Cells 80–250 μ long, 5–6 μ broad, rectangular in girdle view, linear-lanceolate in valve view.

Species 4. **Nitzschia delicatissima** Cleve
(24, 1897*a*, pl. 2, f. 22).

Chains very similar to *Nitzschia seriata*, but much more slender. Length of cell 32–85 μ, width 1·5–2·5 μ. Keels slightly excentric. Puncta 14–25 in 10 μ. No striations visible.

Species 5. **Nitzschia closterium** (Ehrenberg) W. Smith (113, 1853, p. 42).

Synonym: *Ceratoneis closterium* Ehrenberg (37, 1841, p. 64).

Cells single, motile, slightly bent. Ends hair-like. Centre lanceolate, containing a central nucleus and two chromatophores. Length of cell 25–100 μ. Keel puncta about 7 in 10 μ.

Reported by Karsten. Met with frequently in the plankton.

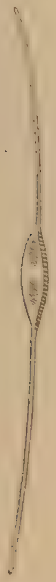

FIG. 96.—*Nitzschia longissima.* Single cell, length 195 μ.

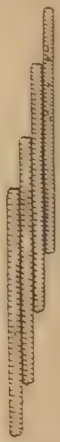

FIG. 97.—*Nitzschia paradoxa.* Valve view, length 82 μ, width 5·2 μ.

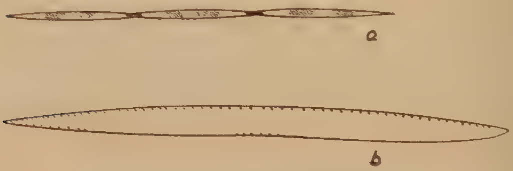

FIG. 98.—*Nitzschia delicatissima.* *a.* Chain of three cells. *b.* Cell in girdle view, length 35·1 μ.

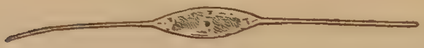

FIG. 99.—*Nitzschia closterium.* Cell 86 μ long. After Cupp, 1943.

VIII. **Surirelloideae** Schütt.

13. Surirelleae Schütt.

Genus: I. *Campylodiscus.*

Genus I. **CAMPYLODISCUS** Ehrenberg

(37, 1841, p. 207).

Valves solitary, saddle-shaped. Valves with a longitudinal central pseudoraphe, that of one valve at right angles to that of the other. Canal pores distinct, usually in parallel rows. Bottom and littoral forms, occasionally found in the plankton.

Species: *C. ralfsii.*

Species 1. **Campylodiscus ralfsii** W. Smith

(113, 1853, p. 30).

Valves nearly circular; canaliculi reaching to the median line. Diameter 40·7 μ to 48·3 μ.

Littoral. Occurs frequently in the plankton.

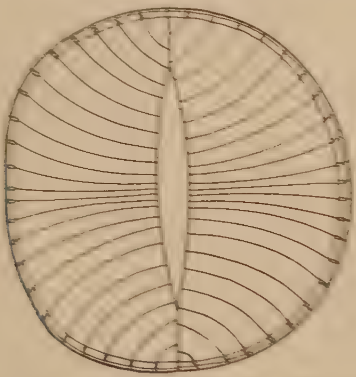

Fig. 100.—*Campylodiscus ralfsii.* Valve view.

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SUBMARINE GEOLOGY AND STRATIGRAPHY

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La Jolla, Calif.

UNTIL about 1935 the study of the ea floor was treated as a step-child by eologists. This was despite the facts hat three-quarters of the earth's surface now submerged and that the bulk of he sedimentary rocks studied by eologists represent deposition in narine environments. In recent years he marine research laboratories at Woods Hole, Mass., and at La Jolla, Calif., have begun extensive programs n submarine geology. These programs ave been assisted by many grants from he Geological Society of America. Beginning in World War II the armed orces inaugurated a large program of cientific research which has included nvestigations of the sea floor in many areas and on a scale which seemed impossible before the war. Research funds rom the oil industry are being contributed increasingly to the program.

A report of progress on these studies of the geology of the sea floor can not ail to emphasize the huge blank areas rom which information is not yet available. However, in recent years a good nany areas have been investigated, particularly around the coasts of the U. S. Even in this short period of time nformation has been obtained which nay prove to have importance in untangling the problems of stratigraphy, and which may help explain the conditions of sedimentation which existed when ancient formations were deposited. Many old geological dogmas have been under attack in recent years. The study of the sea floor has contributed to these attacks. Many of our findings are proving to be irreconcilable with preconceived notions of marine conditions. Since these discoveries may have a considerable bearing on oil exploration both on the lands and on the shallow continental shelves adjacent to the lands, some of the innovations will be considered.

Outward Gradation

It has been a common assumption among geologists that coarse sediments are deposited near shore in shallow water and that the sediments become finer as one proceeds out from the shore. The investigations of the continental shelves have shown few areas where such a gradation exists. Off many coasts we have found silty sediments on the inner shelves which, if preserved, would become future shales; whereas we have found sands on the outer shelves which would become sandstones. According to the bottom character notations on hydrographic charts, this seemingly anomalous relation is the rule rather than the exception off the large rivers of the world. Striking examples

RECENT YEARS have brought increased studies of the geology of the sea floor. Investigations have been made in many areas, especially around the coast of the U. S. Information has been obtained which may be important in untangling problems of stratigraphy and help explain conditions of sedimentation when ancient formations were deposited. A contribution from the Scripps Institution of Oceanography, New Series No. 452, this work represents in part the results of research carried out for the Office of Naval Research under contract with the University of California.

are found on the broad continental shelves off the large rivers of Asia.[1] In many areas there are irregular patches of alternating coarse and fine sediment extending entirely across the shelf and often terminating with the coarse material at the break in slope. In some places the coarse sediment occurs on submerged shelf hills and the fine sediments are found in hollows.

In contrast to the open continental shelves, partially or entirely protected bays and gulfs of large size have a semblance of sediment gradation with sandy zones predominating along the shore and muddy sediments in the central portions. However, even in these areas there are many exceptions to this rule. For example, coarse sediment zones are found in the relatively deep entrances to bays and in some places these coarse zones extend well inside the bay entrances, as is the case in San Francisco Bay.[2]

Several possible explanations for the absence of decreasing grain size on the shelf away from the shore can be considered, although there is no assurance that any of these is the principal cause. In areas where gravel or even cobble deposits are found well out on the shelf, the explanation appears to involve an inherited sediment which has not been covered by recent sediments. For example, the exposure of the continental shelves during the epochs of lowered sea level of the glacial period, when ocean water was stored in the great ice caps, allowed rivers to carry gravels and other coarse sediment out onto the shelves. Subsequent submergence may have left these gravels exposed in areas where currents have been sufficiently strong to prevent deposition. Even the sands of the outer shelves may be explained in this way, although it is somewhat strange if the many vast areas of sand of the outer shelves have not received sediments during the thousands of years of post glacial time.

The great sand deposits of the outer Asiatic shelves may be the result of the powerful currents which are known to exist in these areas. If sand is carried across the shelves from time to time, as seems likely from our sediment trap studies and as is indicated by the layers of sand in cores of deep areas outside the shelves, this sand may be accumulating slowly on the outer shelves. The conditions which bring the sand no doubt also transport large quantities of mud, but the mud may be kept in suspension in these outer zones, whereas it may be deposited near the shore in cases where currents are milder and where the quantities of mud may be so large as to favor deposition. Cores have not yet been made in the sand zones of the outer shelf. In fact, coring in sand requires special devices which are to date only in a developmental stage. Such cores, when they are obtained, should tell whether or not the sand is a lag concentrate of an underlying muddy sediment.

Continental Shelves and Wave-built Terraces

An idea long held by geologists has been that the continental shelves have been built out over the deep sea bottom as wave-built terraces (Figure 1). All shelves which have been built out in this way should lack consolidated rock except near the shore. Also, oil wells which have been sunk in the deltas or sand bars which have been built out over the shelf should penetrate through formations of relatively recent age which have indication of increasing depth of deposition with increasing depth in the wells until they reach true pelagic material comparable with that of the adjacent deep water. However, shelf investigations and the core drill evidence are both unfavorable to the wave-built terrace concept. Rock is very common on the outer shelves, particularly at the break in slope. Off the California coasts investigations show that true ledge rock occurs at innumerable places on the

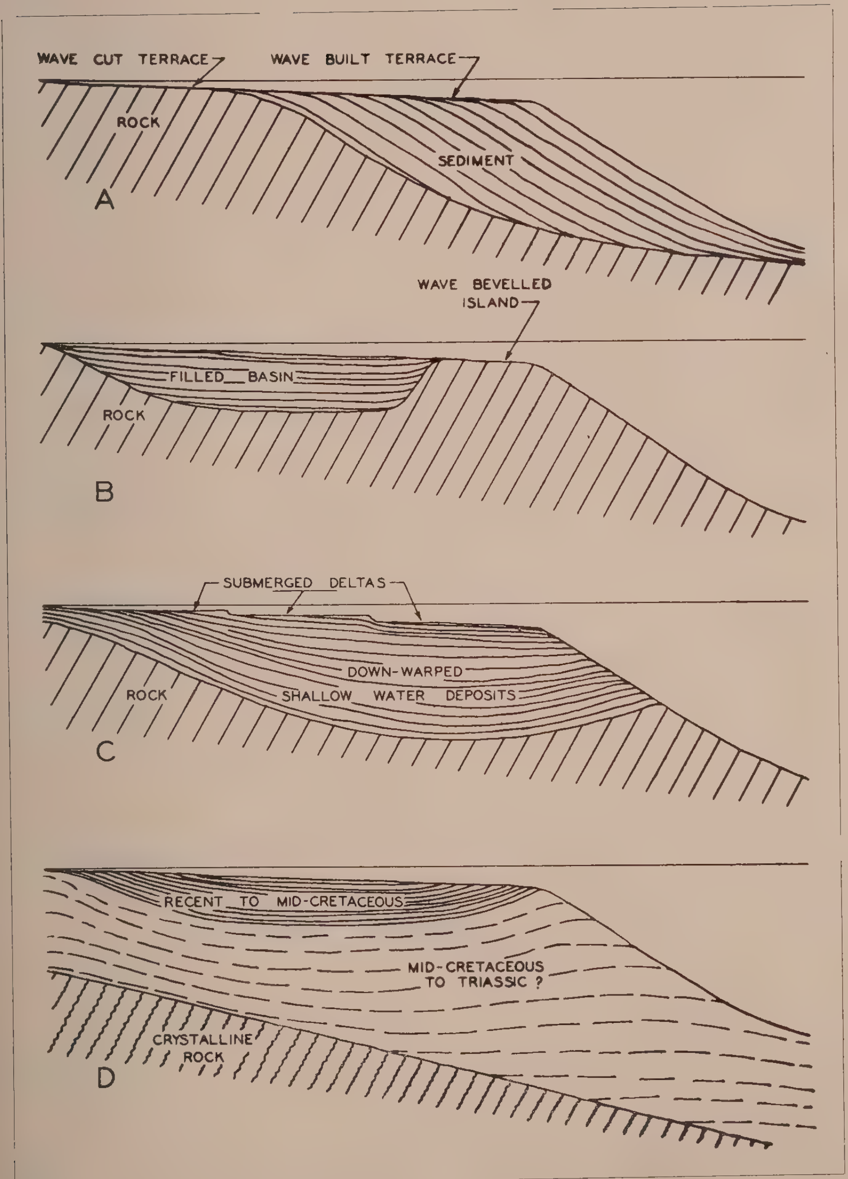
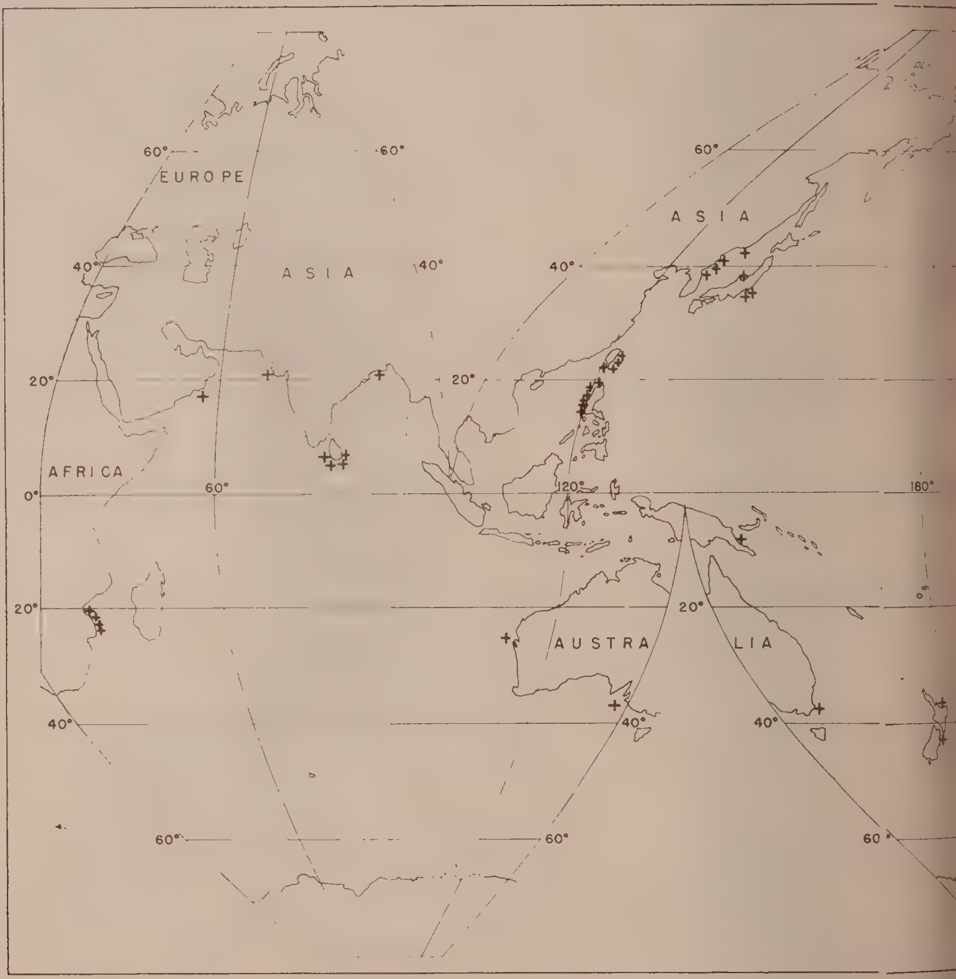

WAVE CUT TERRACE
WAVE BUILT TERRACE
ROCK
SEDIMENT
A
WAVE BEVELLED ISLAND
FILLED BASIN
ROCK
B
SUBMERGED DELTAS
DOWN-WARPED
SHALLOW WATER DEPOSITS
ROCK
C
RECENT TO MID-CRETACEOUS
MID-CRETACEOUS TO TRIASSIC ?
CRYSTALLINE ROCK
D

FIGURE 1. Illustrating various modes in which the continental shelf could have been developed. D represents an interpretation of the geophysical data obtained by Maurice Ewing.


EUROPE
ASIA
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AFRICA
AUSTRALIA
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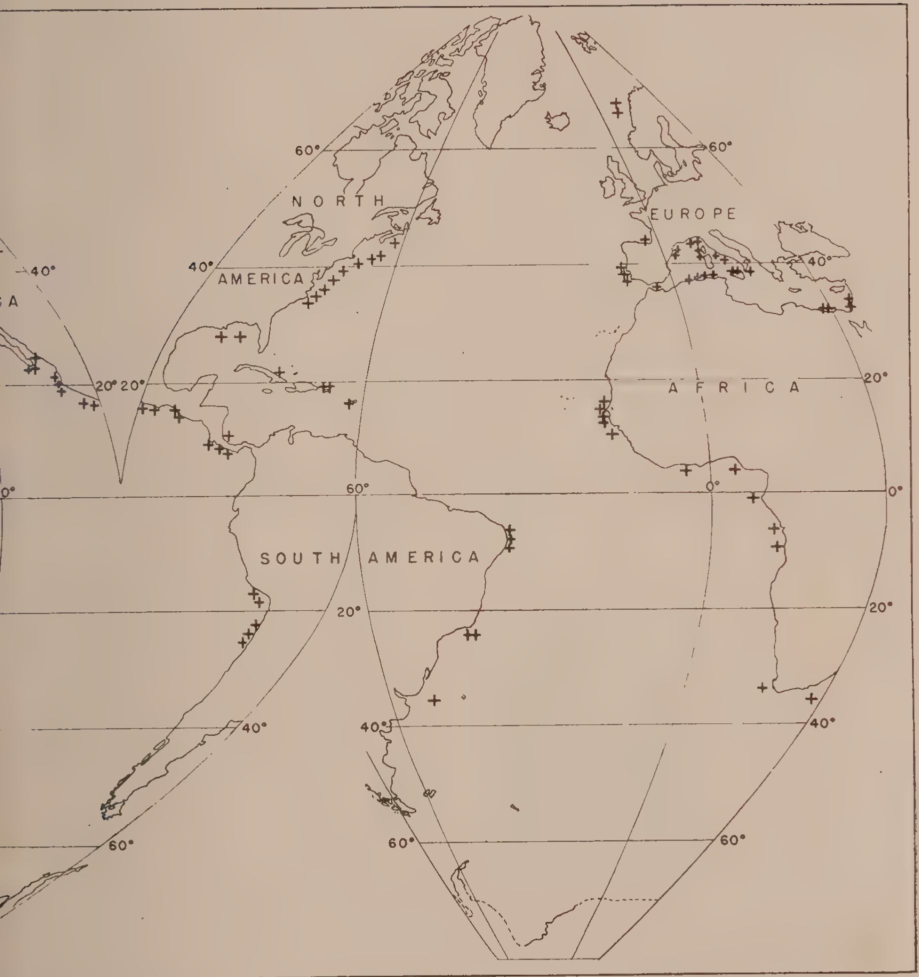
120°
180°
20°
20°
40°
40°
40°
60°
60°
60

(From Journal of Marine Research, Vol. VII. p. 662.

FIGURE 2. The world distribution of submarine canyons. Each cross indicates one or a group c canyons. Many areas lack adequate soundings for the determination of canyons.

outer shelf. Off the east coast rock has not been encountered at the surface, but has been dredged and photographed at moderate depth from a number of submarine canyons which cut the shelf margin. Also a Standard Oil Company (N.J.) well, drilled into Cape Hatteras where a cuspate foreland has built al most entirely across the shelf, has re vealed Tertiary and even Cretaceou formations at moderate depths.[3] Simi larly, rock is indicated by the bottor notations of nautical charts on the oute shelves off innumerable foreign area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60°

us other interpretations of shelf are indicated in Figure 1.[4]

ria for Distinguishing Deep and Shallow Water Formations

a basis of discussion one can con- deep water deposits as those d at depths of 1000 feet or more. care should be exercised in as- g a formation to either a deep or llow water origin. Probably some e bentonitic foraminifera assemblages can be considered reliable depth indices at least for Recent and Pliocene depth zones, but many of the other commonly applied criteria are subject to uncertainty. For example, recent discoveries indicate the presence of sand formations, of ripple marks, and even of cross bedding in sediments lying on the ocean floor at great depth.

Sand layers have been obtained in cores from various basins off California and Lower California at depths ranging up to a mile below sea level. Some of the deep sand contains foraminifera which according to Natland[5] have an assemblage characteristic of the depths now existing in the area. This discovery appears to rule out the possibility that the sand was deposited in shallow water and subsequently submerged. Henry Stetson and Maurice Ewing have both found clean sand layers in their cores from the deep western Atlantic. These cores come from relatively low latitude where ice rafting is most improbable. Stetson also found deep sand layers in the Gulf of Mexico at depths of over 12,000 feet. Hans Pettersson reports sand layers in cores from the deepest portions of the eastern Atlantic obtained by the recent Swedish *Albatros* expedition. It may be that some of this coarse sediment is indicative of great changes in level or even of some type of rafting, but a more likely explanation is that the sand was carried to its present location either by ocean currents or even by great wind storms.

About the Author

DR. FRANCIS P. SHEPARD has engaged in marine research work since 1923 and is an international authority on marine geology. He was a member of the Geological Department, University of Illinois from 1922-42; served with the University of California Division of War Research, 1942-45, and in 1945 joined the Scripps Institution of Oceanography where he is now professor of submarine geology.

The existence of ripple marks at depths somewhat in excess of 1000 feet has been reported by Maurice Ewing and by R. S. Dietz. It seems unlikely that these could be due to wave action unles possibly they represent the effect of tsunamis or internal waves. On the other hand, current ripples seem quite possible at almost any depth. To date the only available information on the measurement of bottom currents[6] gives no indication that these currents decrease in deep areas. It is not unlikely that bottom photography will reveal their presence at much greater depths as soon as more bottom photographs in deep water, particularly on banks and seamounts can be obtained.

There is little evidence as yet concerning cross bedding. However, cross bedding was discovered in a core near the center of the Gulf of Mexico.[7] This zone, like the deep water sand layers, may represent large submergence, but its occurrence at only a small depth below the sea floor makes it seem more likely that it was formed at water depths close to those now existing.

Submarine Slumping

Various articles have been written about landslides and slumping on the sea floor. However, the full significance of this process as a cause of structures and of stratigraphic traps may have been underestimated. Investigations of the sea floor have yielded evidence which suggests that slides or mud flows are common occurrences on slopes of the order of 10 degrees, particularly in areas where the bottom deposits contain mud. A close check on slopes of this kind in the submarine canyon heads near La Jolla, Calif., has led to the discovery of three of these slumps in three different canyon branches during a period of 18 months. The soundings in this area showed deepenings up to ten feet and averaging six feet over an area of at least 50,000 square feet.

The steep fronts of coral reefs form another environment where sliding is known to take place. The intensive studies of Bikini atoll, according to R. D. Russell and K. O. Emery, give evidence of the sliding of large blocks of reef material down the slope. Since these masses are cavernous and since they may slide into an environment of much lower porosity, it is not difficult to imagine the development of future stratigraphic traps along the fronts of coral reefs. In fact, wherever the coral talus is covered by fine sediments, a favorable location for oil accumulation is present.

Along other types of submarine slopes slides may bring relatively coarse material out into an environment where the normal deposits are silt and clay. In Hall Canyon, near Ventura, Calif., Natland[8] has found conglomerates which are interbedded with shales containing a deep water foraminiferal assemblage. One should not overlook the possibility that these conglomerates were carried to their present location by slumping action on a steep sea floor at the edge of cobble deltas. Slumping may occur even on very low angle slopes. Mud flows have taken place on land along slopes of 1 degree and sediments obtained in the Black Sea on slopes of 1 degree have indications of slumping.[9] During the accumulation of ancient marine sediments there must have been many environments where depositional slopes were steep enough for marine slumping. For example, the margins of ancient coral reefs, the sides of old geosynclines, and even the fronts of deltas may have provided the requisite conditions. Some of the confusion from the interpretation of coarse sediments as beach or near-shore deposits may have come from the sliding of the coarse material out along submarine slopes. It is even possible that the material in the process of sliding may become coarsened due to the setting up of turbidity currents along the bottom which would tend to carry away the fines and leave a concentrate of the sandy portion of the slumped material. An explanation of this sort may account for the abundance of sand and even gravel along the axes of submarine canyons at considerable depths and at great distances from the shore.

Instability of Supposedly Stable Coasts

In attempting to understand the conditions of the remote past, it is important to be familiar with recent geological history. We know that during the last million years there has been a series of large continental glaciers and that some mountain ranges have been formed or at least greatly elevated during this period, but it has been generally assumed that most areas have been relatively stable. However, the investigations of the sea floor suggest a different history. In almost every area where samples or detailed soundings have been obtained in deep water, some type of evidence has been found suggesting submergences of the order of one or more miles. Furthermore, there are compelling lines of evidence which indicate that these changes of level have taken place either during the Pleistocene or in the late part of the Tertiary. By far the best evidence of submergence comes from the finding of huge submarine canyons along the continental slopes off the various continents of the world (Figure 2). These canyons have all of the characteristics of river cutting. They have the steep sides and relatively narrow floors characteristic of topographic youth. The canyons extend to depths of many thousands of feet; in fact they may be traced in some places to the very bottom of the continental slopes. The most surprising feature about the submarine canyons is that they are found as commonly off the supposedly stable coasts as they are off areas of known tectonic activity.

In addition to submarine canyons there are other lines of evidence suggesting large scale submergence. Several topographic highs in the deep ocean have been dredged and most of these have yielded rounded pebbles or cobbles which were probably rounded in shallow water. In some places shallow water faunas are found in cores in deep areas, although they may have been transported to their present environments. Drillings into four coral atolls have shown that shallow water faunal assemblages extend down to the bottom of the holes at depths of 1000 to 2500 feet.[10]

The significance of these large changes is hard to evaluate at present, but it seems likely that we must revise our ideas about stable coast lines. Along the same line of reasoning one might inquire into the tenability of the ideas that geosynclines and other basins of deposition underwent a slow and orderly sinking. Possibly some of the large scale movements such as are indicated by marine investigations took place also in the more remote geological past.

The lines of evidence considered in this paper suggest that care should be exercised in drawing freely on old but poorly established dogmas of geology. The field of sedimentology awaits more evidence of what is going on in the present day basins of sedimentation before interpretations of ancient marine conditions can be made with much assurance.

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Contribution No. 453

REPORT ON BEACH STUDY IN THE VICINITY OF MUGU LAGOON, CALIFORNIA

TECHNICAL MEMORANDUM NO. 14
BEACH EROSION BOARD
CORPS OF ENGINEERS

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Contribution from the Scripps Institution of Oceanography, New Series, No. 453

FOREWORD

This paper was prepared by D. L. Inman of the Scripps Institution of Oceanography. The report first appeared in limited issue as Submarine Geology Report No. 5 of the Scripps Institution of Oceanography, University of California. It it believed that the findings of the investigations reported herein are of sufficient value to merit publication at this time.

The opinions and conclusions expressed by the author are not necessarily those of the Board

The authority for publication of this report was granted by an Act for the improvement and protection of beaches along the shores of the United States, Public Law No. 166, 79th Congress, approved July 31, 1945.

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REPORT ON BEACH STUDY IN THE VICINITY OF MUGU LAGOON, CALIFORNIA

Abstract

Investigation and study indicate that the beaches and sand spits bordering Mugu Lagoon are not stable, and that improvements in this area should be undertaken with caution. Any changes will tend to upset the natural beach equilibrium and in some cases may result in further depletion and erosion of the narrow spits bordering the lagoon.

Longshore current studies showed that the complex bottom topography over the Mugu Submarine canyon heads gives rise to currents that may be opposed in direction to the currents along the straight beach northwest of Mugu. The angle of wave approach and the "piling up" of water at wave convergence points appear to be the controlling factors in determining the direction of flow of the longshore currents.

The effect of (1) spring tides, (2) high waves, and (3) direction of the longshore transport of sand on the stability of the spits bordering Mugu Lagoon is discussed.

Introduction

As a result of an investigation of the beaches in the vicinity of Point Mugu, California, information was obtained which appeared to have a direct bearing on the beach studies under Navy contract N6ori-111 at Scripps Institution of Oceanography. Accordingly, the results of the investigation have been worked into a general report.

The purpose of the investigation was to determine the relative stability of the present beaches and sand spits, and to make recommendations for the preservation of the beaches; both as regards natural processes of erosion and deposition, and certain man-made changes, such as dredging of the lagoon, that are contemplated in this area.

The investigation was primarily concerned with (1) the relative effects of waves and longshore currents in transporting sand along the straight sections of the beach in the western portion of the area, and around the complex bottom topography near the submarine canyon heads; and (2) the effects of waves and tidal action on the stability of the narrow spits at the mouth of the lagoon. A series of longshore current and beach observations were made on 18 and 19 December 1948, and on 8 and 9 January 1949. In conjunction with these observations, nine wave refraction diagrams were constructed as an aid in interpreting the effects of waves of various periods and directions of approach on the beaches in this area. A study was made of the beach and shore line changes; historic changes were obtained from a comparison of recent and early surveys, and recent changes were obtained from beach profiles and from repeated aerial photographs taken over a period of several years.

Description of the Area

Mugu Lagoon is a 4-mile-long tidal lagoon situated in the southeastern coastal portion of the Oxnard plain, approximately 8 miles from Oxnard, California, (see figures 1 and 2). The Oxnard plain extends for 17 miles along the coast and lies between the Santa Ynez and the Santa Monica Mountain ranges. It extends inland for approximately 8 miles and has an average elevation of about 30 feet. The plain is bordered on the north by the Ventura River, and is traversed by the Santa Clara River and Calleguas Creek. The landward portions of the plain are formed from flood deposits of the latter two streams. Mugu Lagoon lies parallel to the coast, immediately west of Point Mugu, at the mouth of Calleguas Creek. It is a shallow lagoon separated from the ocean by a broad sand bar in its western one-third, and by two narrow spits converging on a shallow channel in its eastern two-thirds.

The area is a structural basin of deposition in which sediments of considerable thickness have accumulated. There are no hard rock outcrops in the coastal region between Ventura and Point Mugu. In general the alluvial fill, of Recent to late Pleistocene age, is about 500 feet thick and is composed of material varying from gravel to clay with the coarser material predominating (5). The alluvium lies unconformably on the San Pedro formation of early Pleistocene age. The latter formation consists of sand and gravel interbedded with beds of silt, and reflects a progressive change from marine to continental deposition (10). Most water wells in this area are less than 260 feet deep and produce from the alluvium and San Pedro formations. Some wells in the southeast part of the area (Point Mugu region) produce water from depths of 1,300 feet or more.

A new fresh water well just east of U. S. Highway (Alt.) 101 and northeast of Mugu Lagoon encountered a sediment fill of approximately 1,500 feet overlying the Miocene basement. The material from near the surface to a depth of 600 to 700 feet is a permeable sand (8).

The coast line bordering the Oxnard district has three distinct trends. The 8-mile section of beach from the mouth of the Santa Clara River to Point Hueneme trends S 25° E, and is backed by a belt of sand dunes one-half mile wide. South of Point Hueneme the coast line bends 27° to the east, and the dune belt narrows appreciably. This section extends for 6 miles to the northwestern end of Mugu Lagoon, where the coast bends sharply to the east and northeast. The sand bar narrows near the mouth of the lagoon.

During recent geologic time, the Oxnard plain has been built progressively seaward by river and marine deposition. The sediments discharged by the rivers have tended to migrate to the southeast under the influence of longshore currents. The predominant westerly wave approach has been effective in setting up this southeasterly longshore migration of sand. Construction of the Hueneme breakwaters at the head of Hueneme Submarine Canyon in 1939 has caused an increased rate of accretion of beach material up coast from the breakwaters, and active erosion of the 4 mile segment of beach southeast of the breakwaters. The beach near the vicinity of the Mugu Pier has also been eroded. Before deposition of the recent dredge fill in the area near the pier, the narrow sand spits marking the mouth of the lagoon were frequently overtopped by high waves. At that time the spits were approximately 225 feet in width and had an average height of about 10 feet above mean lower low water.

The submarine contours off the Oxnard plain are essentially parallel to the coast except where interrupted by a few submarine canyons (14, chart I). The two largest canyons, Hueneme and Mugu, traverse the continental shelf and extend shoreward to the beach. Mugu Submarine Canyon (figure 4) is located just seaward of Mugu Lagoon and extends for 9 miles in a southerly direction, where it enters the Santa Monica submarine basin. This canyon has two heads; an east branch extends shoreward to a point which lies 2,000 feet east of Mugu Pier, and a west branch extends shoreward to a point 1,000 feet west of the pier. Both Hueneme and Mugu submarine canyons are deep and have been a major factor in the configuration of the coast line in this area.

Previous Investigations and Surveys

The offshore area in the vicinity of Mugu Lagoon was surveyed by the U. S. Coast and Geodetic Survey in 1856, 1878, and 1933. The soundings from the first of these surveys showed a nearshore submarine depression in a position comparable to the present heads of Mugu Submarine Canyon. A 120-foot shoal bar extending southeast from Laguna Point (near Bench Mark Estera) separated this depression from the seaward extension of the present canyon. This same feature is shown on the 1878 chart, however, the position of the soundings indicate that they were obtained from the 1856 survey. While the 1933 survey indicated a shoal area southeast from Luguna Point, it did not extend across the canyon, which was 360 feet deep at that point. The latter survey had sufficient soundings to assure that no such bars existed in 1933.

The Corps of Engineers, U. S. Army took a series of 57 beach profiles from the mouth of the Santa Clara River to Mugu Lagoon in September and October 1938 and repeated most of them in July and August 1948. Four of these profiles were taken in the area near Mugu Lagoon (1); two on the shelf west of Mugu Pier between Bench Marks Estera and Dune, and one at each canyon head. Comparison of the beach profiles near Bench Mark Dune showed very little change over the 10-year period. The one near Bench Mark Estera showed a horizontal recession of 130 feet in the upper portions of the foreshore, and a fill in the lower portions. Both canyon profiles showed a horizontal cutting back of the foreshore of approximately 50 and 80 feet respectively. These beach profiles are part of a detailed report made by the Corps of Engineers (1) covering all phases of shore protection in the vicinity of Port Hueneme, including recommended procedures for rectifying the sand loss caused by the Hueneme jetties. The above survey was very helpful in the preparation of this report, and frequent reference will be made to it.

On 8 January and 22-24 April 1949, offshore surveys were made in the vicinity of Mugu Lagoon by Shepard and Inman (to be published by Scripps Institution). A series of sounding lines were taken and over 60 bottom samples obtained. Comparison of these soundings with the U. S. Coast and Geodetic survey of 1933 showed indications of considerable depth changes in areas near the canyon heads where the bottom slopes are steep. Deepening was indicated near Mugu Pier, and shoaling near Bench Mark Estera (west of the pier) and near the lagoon channel entrance.

The surface topography of the Hueneme Quadrangle was surveyed by the U. S. Geological Survey in 1901, and the survey was revised by the Corps of Engineers in 1941 and 1943. Figure 17 shows a comparison of the early surveys between 1856 and 1933 indicating changes in the shore line. Table 1 gives a list of published maps and charts used in the preparation of this report. In addition to this list, several topographic maps of this area were prepared by the Parsons Aerojet Company of Los Angeles in 1948, with scales of 1 inch equal to 100 feet and 1 inch equal to 400 feet. A contour map of the entrance to Mugu Lagoon with a scale of 1 inch equal to 100 feet was prepared in 1940 by R. D. Stowell of the Geology Department of the University of California at Los Angeles. Extensive use has been made of aerial surveys flown by the Navy and private companies.

Wind

The prevailing winds in the Mugu area are from the west and north, although there are rather frequent "Santa Ana" winds that blow across the Oxnard plain from the east and northeast. A wind rose showing the direction and strength of wind, as measured at the Point Mugu Air Station, is shown in figure 3. Local wind waves and chop set up by the westerly winds may cause a southeast drift of beach sand.

Both the northwesterly and easterly winds reach sufficiently high velocities to cause deflation of beach sand. The northwesterlies cause a loss of sand from the beaches to the back country. This is illustrated by the extensive belt of dunes backing the beach from the mouth of the Santa Clara River to Mugu Lagoon. In the area northwest of Hueneme the direction of the prevailing winds is indicated in aerial photographs by the southeast alignment of sand dunes that have been built around shrubbery.

The large dune back of the pocket beach 2 miles east of Point Mugu is further evidence of the effect of onshore winds in causing deflation of beach sand. At this point beach sand has blown across the highway and has formed a dune several hundred feet high against the base of the mountains.

The stronger of the "Santa Anas" cause some sand to be lost from the beach and deposited in offshore waters. Observations during the morning of 19 December 1948 indicated that at least an inch of sand had been removed by the wind since the previous afternoon from the higher portions of the sand spits at Mugu. It was noticed that the height of stratified sand in the lee of pebbles and debris was 1 inch above the surrounding surface. Records at the Mugu Air Station showed that the wind was from the northeast with an average velocity of 12 miles per hour, although gusts of 25 miles per hour were recorded.

Waves

In an investigation of the effect of waves on a beach or coast, it is necessary to know the nature and direction of the waves to which the shore line is subjected, the percentage of the time that the shore line is exposed to each wave type, and the effect of nearshore bottom topography in refracting the waves.

Exposure of Mugu to Wind Wave and Swell. - A diagrammatic illustration of the types of waves to be expected from the various generating areas, along with wave roses indicating the direction of wave approach and the height of waves from each season, are given in Figures 2 and 3. The wave roses were derived from meteorological records of the northern hemisphere covering a 3 year period (12) and probably give a statistically reliable representation of the swell approaching from the west and northwest. However, they do not include the long-period swell that comes from the southern hemisphere, nor from the Mexican and tropical storms. While these latter waves are not as frequent as the northwesterly approaching waves, they have caused damage along the southern California coast. For example, in September of 1939 the San Pedro breakwater was damaged by large waves from a tropical storm originating off the coast of Baja, California, and in April of 1930 a long-period swell from the southern hemisphere caused the displacement of 20,000 tons of superstructure stone from the Long Beach breakwater (2).

Waves approach this portion of southern California most frequently from the northwest (figure 3). However, Point Conception and Point Hueneme protect the beaches at Mugu from all swell approaching from a direction north of N 72° W, and the channel islands give protection from west to S 68° W. This limits the effect of northwesterly approaching waves at Mugu to an 18° arc between Point Conception and the channel islands. The long-period waves from the Gulf of Alaska storms are further restricted, and are limited to a 10° arc. Laguna Point, west of Mugu Pier, further protects the Mugu sand spits from westerly approaching waves.

The beaches at Mugu have comparatively little protection from the south and southwest, although the southern coastal islands offer some protection from long-period waves that originate in the southern hemisphere and in Mexican waters. The beaches are exposed to local fronts from S 20° E to 68° W and to local storms for a 135° arc from S 67° E to S 68° W.

The only waves approaching the beaches from within the protected sectors shown in figure 2 are local wind waves. Since the fetch is short, these waves have short periods and usually have low amplitudes.

Wave transformation in shallow water. - The profiles of ocean swell in deep water are long and low, approaching a sine wave in form. However, as waves enter shallow water the wave velocity and length decrease, the wave steepens and the height increases until the wave train consists of peaked crests separated by flat troughs. Near the breaker zone the process of steepening is accelerated so that the breaking wave may attain a height several times greater than the deep-water wave. This transformation is particularly pronounced for long-period swell from a distant storm. The profiles of local storm waves show considerable steepness even in deep water so that the shallow water steepening is not as pronounced (9).

The shallow water transformation of waves commence at the depth where the waves "feel bottom." This depth is equal to one-half the deep-water wave length (where the wave length is the horizontal distance from wave crest to crest). The deep-water wave length in feet is given by the relationship:

$$L_0 = 5.12\ T^2$$

where L_0 is the deep-water wave length and T is the wave period in seconds.

Also under shallow-water conditions the waves are subjected to refraction, a process in which the wave crests tend to parallel the depth contours. For straight coasts with parallel contours, this decreases the angle between the approaching wave and the coast, and cause a "spreading" of the energy along the crests. The wave height is decreased by this process but the effect is uniform along the coast. A submarine canyon or depression causes waves to be refracted or bent in such a manner that waves over the canyon will diverge, causing the waves to decrease in height and the line of wave crests to be convex toward the shore. Waves will converge on either side of the canyon or over a ridge, causing the wave height to increase and the line of wave crests to be concave toward the shore. The amount of wave refraction and consequent change in wave height and direction is a function of both wave period and direction of approach.

Wave refraction diagrams. - A wave refraction diagram shows the effect of shoal water on a form and spacing of wave crests (4). The diagrams may be interpreted as showing the consecutive positions and forms of one wave crest at increasing intervals of time, or as a synoptic picture of a group of wave crests.

The concentration of energy relative to the energy per unit crest length of the deep-water wave may be determined graphically by the spacing of wave orthogonals, where orthogonals are lines drawn perpendicular to the wave crests at all points and indicate the direction of wave propagation. The relative amount of convergence or divergence (and hence the increase or decrease in relative energy) due to wave refraction is determined by the ratio of the distance S_o, between wave orthogonals in deep water to the distance S_b between the same orthogonals at the point where the waves break.

The breaker height H_b is proportional to the cube root of the wave energy. Therefore, a refraction factor, K_b for breaking waves is defined by the relationship

$$K_b = \sqrt[3]{S_o/S_b}$$

Discussion of wave refraction diagrams. - Nine wave types with differing periods and from different directions were chosen as representative of the waves approaching the Mugu area. These wave types were chosen on a basis of (1) exposure of the Mugu area to waves (figure 2), (2) the most common directions of wave approach during each season (figure 3), and (3) the relative amount of work performed by waves of a given period and deep-water direction of approach (12 figures 1D - 7E). The refraction diagrams drawn for these directions and periods are indexed on figure 2 and reproduced on figures 4 -12.

A graphic summarization of the refraction factors and angles of wave approach obtained from the wave refraction diagrams is given in figure 13. The two wave refraction diagrams (figures 4 and 5), chosen as representative of the waves approaching Mugu through the Santa Barbara Channel, in general indicate a reduced breaker height near Mugu Pier and the lagoon mouth. Waves from other directions all showed some convergence at one or more points along the sand spits. Inspection of the summary of refraction diagrams indicates that there are five localized areas that are subjected to wave convergence from four or more of the nine periods and directions investigated. These areas are as follows:

1. A broad sector along the straight beach between Bench Marks Mag and Dune (6,000 to 10,000 feet west of Mugu Pier). The small submarine ridges and canyons west of Mugu Canyon cause the longer period waves to converge, resulting in refraction factors greater than 2.0 in some cases (figure 11).

2. A narrow sector just east of Bench Mark Estera (2,500 feet west of the pier). The submarine sand ridge east of Estera and the west head of Mugu Canyon causes convergences at this point.

3. A 1,300-foot section of beach just east of Mugu Pier (200 to 1,500 feet east of the pier). The ridge separating the two branches of Mugu Canyon causes convergences in six out of the nine cases investigated.

4. A 1,000-foot section near the lagoon channel entrance (3,500 feet east of the pier). This convergence is caused by the small submarine ridge east of the Mugu Canyon heads.

5. A broad sector along the Point Mugu headland (8,500 feet east of Mugu Pier to Point Mugu).

It should be noted that the beach areas subjected to wave convergences over a submarine ridge change with changing wave period and direction of approach much as the shadow behind a solid object moves when the direction of illumination is shifted. The ridge between the heads of Mugu Canyon serves as a good illustration. Waves of 6-second period from the southwest (figure 8) cause a convergence concentrated at a point 1,500 feet east of the pier, while waves of a similar period from the south (figure 10) converge 500 feet from the pier. Thus waves with periods and directions differing from those selected may result in convergences of different intensity and at different points along the beach.

Past experience has shown that points of wave convergence such as the five listed above are subject to a much greater degree of beach cut and fill than similar areas where the intensity of wave attack is reduced (13, figure 38). The effect of wave refraction and angle of approach on sand transport will be discussed in a later section.

Tides

The tides in the vicinity of Mugu ocean pier are characterized by predominant semidiurnal constituents, giving rise to two high and two low tides each day. The mean range of tides, or the difference in the height between mean high and mean low water, is 3.7 feet. The diurnal range, or difference in height between mean higher high water and mean lower low water, is 5.3 feet. The extreme tidal range is about 9.5 feet, with an extreme high water of about 7.5 feet above mean lower low water. High waves, and local storms and winds may cause the water level to rise above the predicted height. These so-called "storm tides" sometimes augment the astronomic tide by several feet.

Spring tides and particularly extreme tides have an important effect on the sand spits in that they allow large waves to erode more effectively and they increase the tidal prism of the lagoon. An increase in the tidal prism causes greater tidal current velocities in and near the lagoon entrance. The increased tidal currents during spring tides are at least partially responsible for the cyclic changes in the position of the lagoon entrance (see figure 19).

Sand Transport and Beach Erosion

The establishment and maintenance of natural sand beaches and related phenomena are the result of a delicate balance between the amount and location of source sand, topography and configuration of the coast line, and the effects of wave and tidal action. Any changes, natural or man-made, tend to upset this equilibrium.

Waves are effective in causing sand to be transported laterally along the beaches by lonshore currents, and in causing movements of sand from the foreshore to deeper water and back again to the foreshore. The offshore-onshore cut and fill of beaches is apparently related to the type of waves to which the beach is subjected (7). Low-amplitude-wave action transports sand from offshore areas and deposits it on the foreshore, thus building the foreshore seaward. High-amplitude waves, and particularly high-amplitude short-period waves (typical storm waves), have just the opposite effect. They cut back the foreshore and deposit the sand offshore. Severe storms may result in a permanent loss of sand from the beaches, particularly where deep water extends near shore as in the case of submarine canyon heads.

Beaches undergo cyclic changes, the most pronounced being the annual cycle. Most beaches along the southern California coast built seaward during the summer months when the waves are typically low, and are cut back during the period of higher winter waves. There are shorter cycles of cut and fill associated with the spring and neap tides and with nonseasonal waves and storms.

The beaches in the Mugu area were studied in the field on the 18th and 19th of December 1948, and 8th and 9th of January 1949. On 18 and 19 December a series of observations were made from Bench Mark Mag to Point Mugu, and on 8 and 9 January from near Mag to the Lagoon Channel mouth. Field investigations consisted of longshore current measurements made with dye and a weighted ball (15) measurement of beach slope and sampling of the beach foreshore material.

Nature of the beach material. - The foreshore beach slope was measured and a beach sample obtained at each of 17 stations during the week end of 18 December 1948. These stations extended from near Bench Mark Mag (7,000 feet west of the pier) to Point Mugu. Fourteen samples were obtained from near Bench Mark Estera to the Lagoon entrance on the 8th of January 1949. The samples were obtained from the upper 2 inches of the beach surface, at a point approximately 5 feet above mean lower low water. Mechanical analyses of the samples were made, and their median diameters and Trask's coefficients of sorting and skewness were obtained (6). The median diameter, sorting, and skewness of the sand, and the slope of the foreshore at each station are shown graphically in figure 14.

Much of the significance of the study of sand types along the beach at Mugu was lost because dredge material from the lagoon was placed on the beach foreshore following the storm of 17 December. The material from the lagoon had a smaller median diameter and was more poorly sorted than the natural beach sand. Its distribution by waves and longshore currents tended to mask the character of the natural beach. The observations on the week end of 18 December were probably not affected to a great extent by the dredge fill, since dredging operations had just started on the beach, and the fill was limited to a small area a few hundred feet east of the pier. However, inspection of the plotted samples indicates that the easterly longshore currents caused the character of the beach to be modified by dredge material for a distance of at least 2,000 feet east of the pier (figure 14). By 8 January the effect of dredge material may have been reflected to some extent in most of the beach samples obtained.

The sand on the surface of the beach foreshore near Mugu had an average median diameter near 0.3 mm. However, in some localities, particularly along the west spit, the upper few inches of sand were underlain by pebbles 20 to 40 mm. in diameter.

In general, the size of the sand on the beach is reflected in the slope of the beach foreshore; gentle slopes being characteristic of fine sand beaches, and the slope increasing for increasing sand size. However, the beach slopes do depend, to a certain extent, on the severity of recent wave attack, since intense wave action not only cuts the foreshore but tends to level the beach. The effect of intense wave attack on the slope of the beach foreshore is illustrated by a comparison of the slopes measured on 18 December with those obtained on the 8th of January. The 18 December beach measurements were made the day following a storm that resulted in extensive cutting of the beaches in the Mugu area. No foreshore beach slopes greater than $5\frac{1}{2}^{\circ}$ were observed following this storm. The 8 January observations were made following a period of relatively low waves and, although the median diameter of the beach sand was nearly the same as before, foreshore beach slopes as great as 11° were measured.

A plot of foreshore slope against the size of the beach sand samples, collected on 18 December after the storm, shows a scatter of points. The 8 January 1949 samples show an increase in beach slope with increasing sand size. Beach sands with median diameters near 0.30 mm. have a foreshore slope of $6\frac{1}{2}^{\circ}$, and sands with median diameters of 0.45 mm. have a slope of 10°.

Longshore current observations. - On an open coast with parallel bottom contours, the direction of the longshore currents caused by a given wave period may be estimated from the direction of wave approach (11). In effect, this principle was used by the Corps of Engineers (1) in estimating that the coast line between Santa Clara and Mugu is subjected to a predominant southeasterly longshore current. However, wave refraction over nearshore deeps (i.e., submarine canyons) may cause longshore currents that at some points are opposed in direction to the prevailing tendency on a straight coast. Further, a change in wave period, even though the direction remains the same, may cause local reversals in longshore current direction in areas bordering irregular submarine topography (15).

The fact that different wave amplitudes and periods may cause reversals in the longshore current was demonstrated by the measurements at Mugu on the 18th and 19th of December and the 8th of January. On the 18th of December, with the exception of a westerly current along a small area near Mugu Pier, the easterly drift was well pronounced along the entire beach from Laguna Point to Point Mugu (figure 15). On this date the waves had a period of about 8 seconds and were approaching from approximately N 85° W. They resulted in breaker heights of 5 feet off Laguna Point and 3 to 4 feet off Mugu Pier. Strong easterly currents were observed off Bench Mark Mag and west of Luguna Point. The currents east of Laguna Point, while maintaining a general easterly direction, were considerably reduced in magnitude particularly near the canyon heads and along the east spit.

On the following day (19 December) the wave period was approximately 12 seconds and the waves were from the southwest. These waves caused 4- to 5-foot breakers off Laguna Point and 1- to 3-foot breakers off the sand spits. In this case there was no measurable longshore current west of Estera or along the eastern sand spit. However, there were both easterly and westerly currents at various points between Estera and the lagoon mouth. In general, these currents had a tendency to converge near the canyon heads.

On the 8th of January 1949 the waves were from the west-northwest and had a period of approximately 7 seconds. These waves resulted in a general easterly longshore current along the entire beach from Bench Mark Mag, past Estera to the lagoon inlet. However, the velocity of the current was considerabley reduced near the canyon heads and along the sand spit near the pier.

The above observations confirm previous observations by Shepard and Inman (15) over similar bottom topography at La Jolla, California. They indicate that the longshore current is dependent not only upon the direction of wave approach but also upon the location of points of wave convergence. Inspection of the longshore current directions and breaker heights of 19 December shows that in general the currents flow away from points of high breakers toward locations of lower breakers. The waves on this date are represented approximately by the refraction diagram drawn for 10-second waves from the southwest (figure 7). Inspection of this refraction diagram shows that wave convergences are indicated for the approximate locations where high waves were measured on 19 December. The longshore currents measured on the 18th of December and 8th of January show a similar tendency for the current to flow away from points of wave convergence.

Thus, if the principle is valid that the direction of longshore currents is dependent upon the location of wave convergence points as well as on the angle of wave approach, then the refraction diagram when properly interpreted becomes an aid in determining the direction of longshore currents. While this principle should be checked for a greater number of wave directions and periods, the observations at Point Mugu and similar observations at La Jolla suggest that this principle is valid. The location of wave convergences and divergences along with the direction of wave approach at the shore line, are plotted graphically in figure 13. Inspection of this figure and the plotted longshore currents (figure 15) indicates that only waves from the west and north of west with periods of less than 8 seconds will result in a continuous easterly transport of sand in the vicinity of Mugu Lagoon; and that, while the high velocity of these currents between Bench Mark Dune and Estera may result in a large amount of lateral sand transport as far as Bench Mark Estera, sand transport around the canyon heads will be much reduced by the lower velocity of the longshore current. It can be expected that waves from all other directions will result in a westerly direction of the longshore current at several places near Mugu Pier and along the sand spits. The reduction in the longshore current at Bench Mark Estera (figure 15, 18 December and 8 January) and the westerly longshore current from the west canyon head to Estera (19 December) may account for the building out of the submarine sand ridge which extends southeast of Bench Mark Estera.

Beach changes from the Santa Clara River to Point Mugu. - In the past, the Santa Clara and Ventura Rivers were the major sources of sand for all beaches between Ventura and Point Mugu. The predominant wave approach from the west set up longshore currents that resulted in an easterly longshore migration of this source sand. In view of the prevailing easterly longshore currents, and the scarcity of sand east of Point Mugu, it is doubtful if significant qualities of sand reached Mugu spits from the east. Also, the small volume of flow and the slight gradient of Calleguas Creek minimize it as a substantial source of sand.

The abrupt change to the northeast in coastal trend near Laguna Point (figure 4) and the narrowing of the wide spit near Mugu pier is probably due to the deep water off Mugu Submarine Canyon. The easterly sand transport has not been sufficient to fill the canyon heads and allow as great a seaward migration of the coast as along the sections of coast bordered by shallow shelves. Slumping within the canyons prevents retention of fill in canyon heads.

A similar change in coastal trend is found at Point Hueneme where the coast turns abruptly to the southeast. In the past, the sand transport around Hueneme and Mugu Canyons was sufficient to maintain the narrow spits off Mugu Lagoon. In June and November of 1939 two jetties at the entrance to Port Hueneme were completed. These jetties extended from the shore toward the deep water at the head of Hueneme Submarine Canyon. Beach profiles taken by the Corps of Engineers in 1938 and repeated in 1948 (1) show an accretion of the beach materials west of the jetties and a progressive depletion of sand east of Hueneme. The beach section extending from the Santa Clara River half way to Point Hueneme showed an accretion of the upper portions of the beach and a loss of material from the mean lower low water line to 20-foot depths. The 17,000-foot section of beach directly northwest of Hueneme experienced an accretion of all portions of the beach down to 30 feet below mean lower low water, which was the limit of the observations. Since the completion of the Hueneme jetties, there has been active erosion in the 4 mile segment of beach southeast of the jetties. Some sections of the beach having been cut back as much as 700 feet. This erosion has made it necessary to construct revetments and sea walls along portions of the area. The Hueneme Wharf and Warehouse Company buildings, east of the jetties, were undermined and partly destroyed in 1943. It seems probable that the jetties have effectively blocked longshore sand migration from the west around the entrance to Port Hueneme, and are causing the sand to be deposited in the deep water at the head of Hueneme Canyon.

From a comparison of the 1938 and 1948 profiles and surveys, the Corps of Engineers have estimated that the amount of longshore sand transport near Port Hueneme was 480,000 cubic yards per year. They have further estimated that the net loss of sand from the beaches between Hueneme and Point Mugu amounted to 1,254,000 cubic yards per year during the ten years between surveys (1).

Four of the beach profiles taken by the Corps of Engineers were in the vicinity of Mugu Lagoon; two were on the broad shelf west of Mugu Canyon (between Bench Marks Dune and Estera) and one at each canyon head. Comparison of the 1938 and 1948 profiles near Bench Mark Dune showed very little change over the 10-year period. Comparisons near Bench Mark Estera showed a recession of 130 feet in the upper portions of the beach and a fill along the lower portions. Both canyon profiles taken in 1948 showed a horizontal cutting back of the foreshore of 50 and 80 feet, respectively.

A comparison of the soundings obtained during an offshore survey in the vicinity of Mugu Canyon on 8 January 1949 with those obtained by the U. S. Coast and Geodetic Survey in 1933 showed indications of considerable depth changes in the areas where the bottom slopes were steep. On the other hand, similar depths were found in the shelf area west of Mugu Canyon where the slopes are gentle. Deepening was indicated near Mugu Pier, and shoaling near Bench Mark Estera (west of the pier) and near the lagoon channel entrance. The deepening near the pier is supported by observations of general beach recession in this area and by the Corps of Engineers' profiles (1). The shoaling near the channel mouth in the east head of Mugu Canyon was probably caused by sand and silt brought seaward by the ebb tide currents flowing out of the lagoon. It should be noted that the 3-fathom contour of the 1933 survey shows a shoal area seaward of the position of the 1856 tidal inlet (figure 17). The extreme shoaling off Bench Mark Estera may be the result of deposition of easterly migrating sand due to a decrease in longshore currents around the lagoon point and over the west canyon head.

The beach near Mugu has experienced two marked periods of foreshore cut since the summer of 1948. On 4 August 1948 the beach was cut back to the buildings bordering the pier, and on 17 December 1948 the beach was cut beyond the buildings, undermining portions of the buildings on both sides of the pier (see fill area in figure 24).

Inspection of the weather maps indicated that there were no storms in the northern hemisphere that would have resulted in high waves at Mugu on the 4th of August. It is probable that this erosion was caused by southern hemisphere swell, augmented by spring tides. The two wave refraction diagrams drawn for long period waves from southerly directions (figures 9 and 11) show minor convergences near the pier.

The 17 December storm resulted in property damage from Rincon to Redondo Beach. An analysis of the weather maps showed that the waves experienced at Mugu on this date were from a coastal front, or local storm, originating south of San Francisco. The analysis indicated that at 0830 on the morning of 17 December the Mugu area was subjected to 8-second period waves with a deep-water wave height of 13.7 feet, and with a direction of approach from S 60° W. No wave refraction diagram for this specific period and direction was drawn. However, refraction diagrams for 6-second and 10-second waves from the southwest are shown in figures 7 and 8. Both of these diagrams show wave convergences just east of Mugu Pier and indicate fairly high waves at the pier. The erosive effect of these waves was also augmented by spring tide.

A profile of the beach and adjacent sea floor taken from the Mugu Pier on 18 December (figure 16) showed the extent of beach cut caused by the 17 December storm. Following this storm, 700,000 cubic yards of material dredged from Mugu Lagoon was placed for approximately 4,500 feet along the west sand spit and on the beach foreshore near the pier (compare figures 23 - 27). Rapid degrading of the beach was shown by the profiles obtained during the periods that dredged material was deposited on the beach adjacent to the pier (19 December 1948 and 17 March 1949). This rapid cutting back of the beach was the result of wave action on the unstable beach slope associated with the artificial fill.

Beach profiles taken from Mugu Pier following the dredging operations have shown a gradual, although consistent, recession of the beach foreshore (compare profiles of 9 June and 11 March 1949, figure 16).

Fluctuations in the Mugu Tidal Inlet

It has been suggested that storm waves tend to produce tidal inlets, that tidal currents maintain them, and that longshore transport of sand closes them (3). This general principle appears valid for the lagoon mouth at Mugu. In this case the tidal currents definitely maintain the channel entrance, the easterly transport of sand tends to cause accretion of the west spit and to build it eastward, and high waves overrun the spits, tending to form new inlets. In figure 21, successive accretion on the west spit is illustrated by the series of small recurved spits on the distal end of the main spit.

Historic changes in the location of the tidal inlet to Mugu Lagoon are illustrated in figure 17 by a comparison of surveys made in 1856, 1901, and 1933. This comparison shows that the inlet migrated approximately 3,300 feet west in the 77 years from 1856 to 1933; 1,800 feet from 1856 to 1901; and 1,500 feet from 1901 to 1933. The exact distances are not significant, since recent surveys show large fluctuations of the inlet. However, it may be significant that the major trend has been to the west, and no fluctuation since 1945 (figures 17 - 20) has placed the inlet any farther east than the 1901 channel. In view of the tendency for the longshore transport of sand to build the west spit eastward, this westerly migration of the inlet may indicate that the supply of sand to the Mugu spits has been gradually diminishing since 1856. This assumption is strengthened by the beach changes indicated on the U. S. Coast and Geodetic Surveys of 1856 and 1933. A comparison of these two surveys (1) shows that the beach between the Santa Clara River and Point Hueneme was built more progressively seaward between 1856 and 1933 than it has in more recent years. However, the surveys showed a slight recession of the beach east of Hueneme and at Mugu Lagoon. This recession may be due to a decrease in the amount of sand transported past the canyon heads at Hueneme. Although the longshore migration of sand tends to fill in the canyon heads, this fill may not keep pace with the rate of beach accretion over the shallow shelves. Thus beach accretion on the shelf near a deep submarine canyon may result in less material being transported across the deeper portions of the canyon, and a consequent decrease in sand supply to down current beaches.

Construction of the Hueneme jetties in 1939 caused a rapid accretion of sand west of the jetties and an apparent decrease in sand supply to the beaches southeast of Hueneme. The decrease in sand supply passing Hueneme is probably reflected in an increased instability in the tidal inlet to Mugu Lagoon.

A comparison of aerial photographs showing the positions of the tidal inlet in March 1945, November 1946, and February 1947 is shown in figure 18. This comparison shows fluctuations of over 1,000 feet between 1945 and 1947.

Effect of spring tides and waves on inlet fluctuations. Spring tides may be an important factor in causing fluctuations in the position of the Mugu tidal inlet. They allow large waves to erode more effectively and they increase the tidal prism of the lagoon, causing greater tidal current velocities in and near the tidal inlet. There was a well-defined bend in the lagoon tidal channel 2,500 feet east of Mugu Pier (figure 1). At this point spring tides caused excessive erosion of the sand spit from the lagoon side, as well as wave erosion from the seaward side of the spit.

A group of 14 aerial photographs of the Mugu tidal inlet were taken between 3 February 1947 and 21 March 1947. A comparison of six of these photographs with the envelope of the daily higher high tides is shown in figure 19. The 3 February photograph shows the tidal inlet to be approximately 4,000 feet east of the pier. Two days later (5 February), just after the highest spring tide, a new channel formed 700 feet west of the original opening. A photograph on 17 February, following the neap tide, showed that the spit built eastward and that the inlet was almost in its original position. The following spring tide resulted in another break-through in approximately the same location as the 5 February inlet (see 24 February, figure 19). However, a photograph taken on 5 March during the next spring tide showed an accretion of the west sand spit, rather than erosion, and further accretion was indicated during the spring tide 2 weeks later in a photograph taken on 21 March. Accretion of the sand spit during these latter two spring tides may have been the result of low waves during the spring tide periods and the relatively small tidal range during the spring tides of 21 March 1947.

The relative positions of the tidal inlet between February 1947 and February 1949 are shown in figure 20 by a comparison of aerial mosaics. On 4 August 1948 high waves and a spring tide caused the channel to break through 1,200 feet west of its previous position. This new location was opposite the sharp bend in the tidal channel 2,500 feet east of Mugu Pier, and is shown approximately by the position of the inlet on 9 September 1948 (figure 20). After this break-through the spit gradually built eastward and the inlet was diverted to its original channel (shown by 15 December 1948, figure 20).

On 17 December 1948 the beaches at Mugu were subjected to high waves from a local storm augmented by a spring tide. This storm resulted in pronounced erosion of the beaches and sand spits and caused a second channel to form in the same location as the 4 August break-through. In spite of the dredged fill deposited on the beaches near the pier, these two channels persisted and continued to increase in size for several months (compare figures 23 - 27).

Conclusions

The field investigation of the beaches and sand spits in the vicinity of Mugu Lagoon, and the study of recent and historical changes indicates that the Mugu spits and beaches have not been stable during historic times and at present exhibit a considerable degree of instability. The recent study of this area by the Corps of Engineers, (1) and the changes in the coast line during recent geologic and histroic times, indicate that the major sources of sand for all beaches between Ventura and Point Mugu were the Santa Clara and Ventura Rivers. The predominant wave approach from the west set up longshore currents that resulted in an easterly migration of source sand. It seems probable that the Hueneme jetties constructed in 1939 have effectively blocked the easterly longshore migration of sand. Present active erosion of beaches east of Hueneme is probably the result of this sand loss. The recent beach changes near Mugu are also probably in part the result of sand loss behind Hueneme jetties and in Hueneme Submarine Canyon. If the beach erosion and instability at Mugu are the result of the interception of source sand at Hueneme, then the beaches in the Mugu area are apt to become even less stable in the future, unless corrective measures are inaugurated at Hueneme.

The predominant sand transport along the Mutu spits is also probably to the east. However, the longshore current study aided by the wave refraction diagrams indicates that the easterly transport is not as great near the Mugu spits as along the straight coast near Point Laguna, and that the currents along the section near the spits are subjected to a greater number of changes in their direction of flow. These changes in the direction of longshore flow may decrease the amount of sand reaching the spits and cause some sand to be transported seaward by rip currents and deposited in the deep water of the canyon heads.

Inspection of the nine wave refraction diagrams indicate that there are five general areas within the Mugu sector that are subjected to wave convergence. Two of these areas, one just east of Mugu Pier and the other off the Mugu tidal inlet, are particularly important in that they allow excessive wave erosion and over-topping of the sand spits near the Mugu Pier and tidal inlet.

Both the northwesterly and easterly Santa Ana winds reach sufficiently high velocity to cause deflation of beach and dune sand in the Mugu area. While the amount of sand lost by deflation is not as great as that eroded by waves, it nevertheless may be important to the total sand budget of this area.

Extreme tides may have an important effect on the sand spits in that they allow large waves to erode more effectively and they increase the tidal prism of the lagoon. An increase in the tidal prism causes greater current velocities in and near the lagoon entrance. Dredging may also increase the tidal prism of the lagoon, but its greatest detriment lies in the fact that the dredged areas will become subject to fill from the sand spits and tidal inlet. The natural tendency of the flood tidal currents is to deposit beach sand in the dredged area of the lagoon and for the ebb currents to deposit beach material in the east submarine canyon head.

There is the possibility of salt water encroachment within the aquifers supplying fresh well water to the Oxnard plain. The probability of accelerating such encroachment by dredging operations should be given consideration. A new fresh-water well within 1½ miles of Mugu Lagoon penetrates 600 to 700 feet of permeable sand which is not protected by an impermeable cover. Dredging will have a tendency to break a natural water seal which may otherwise exist owing to the accumulation of fine material on the natural lagoon bottom.

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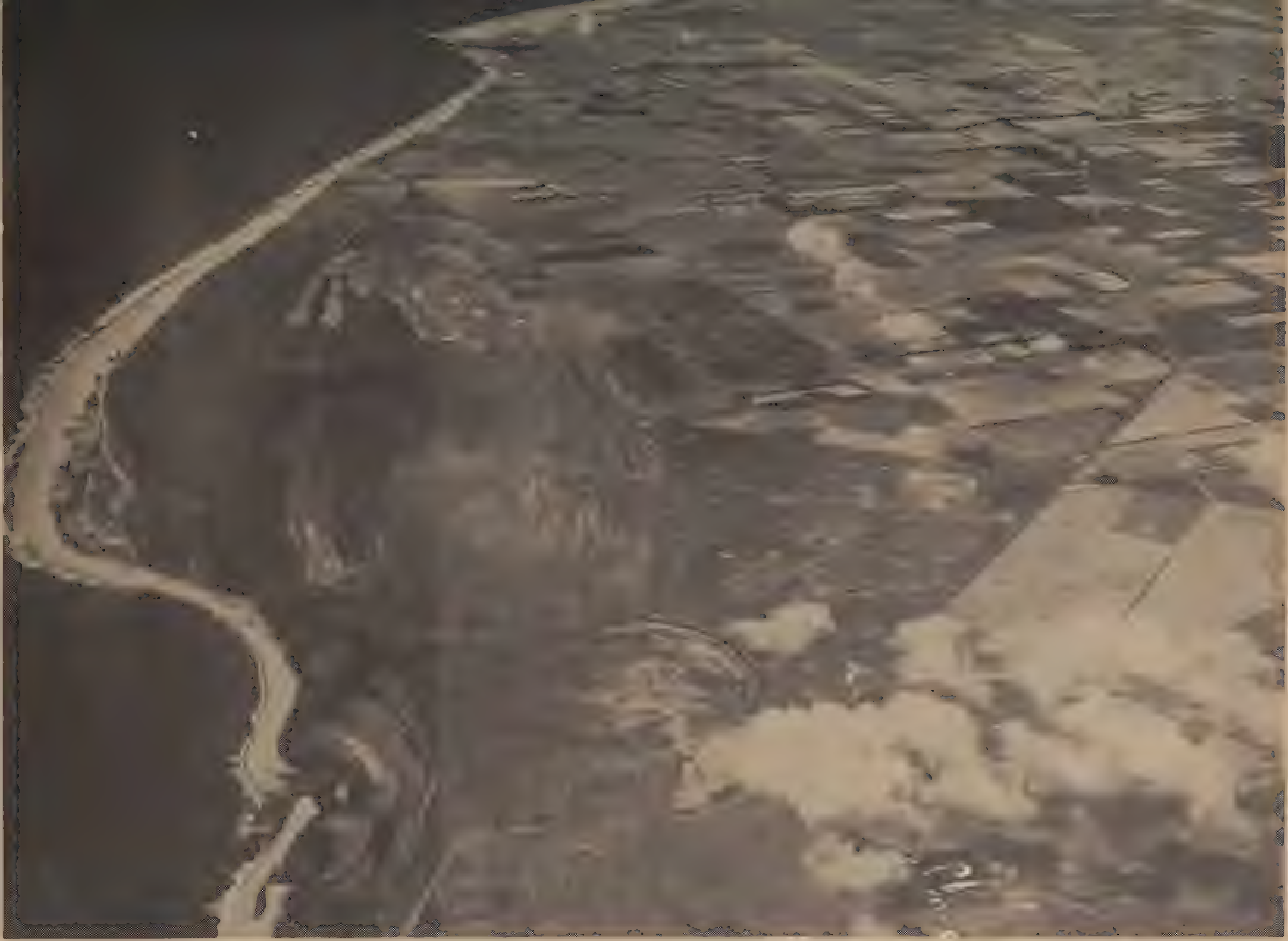
TABLE 1

Charts and Maps Used in Preparation of this Report

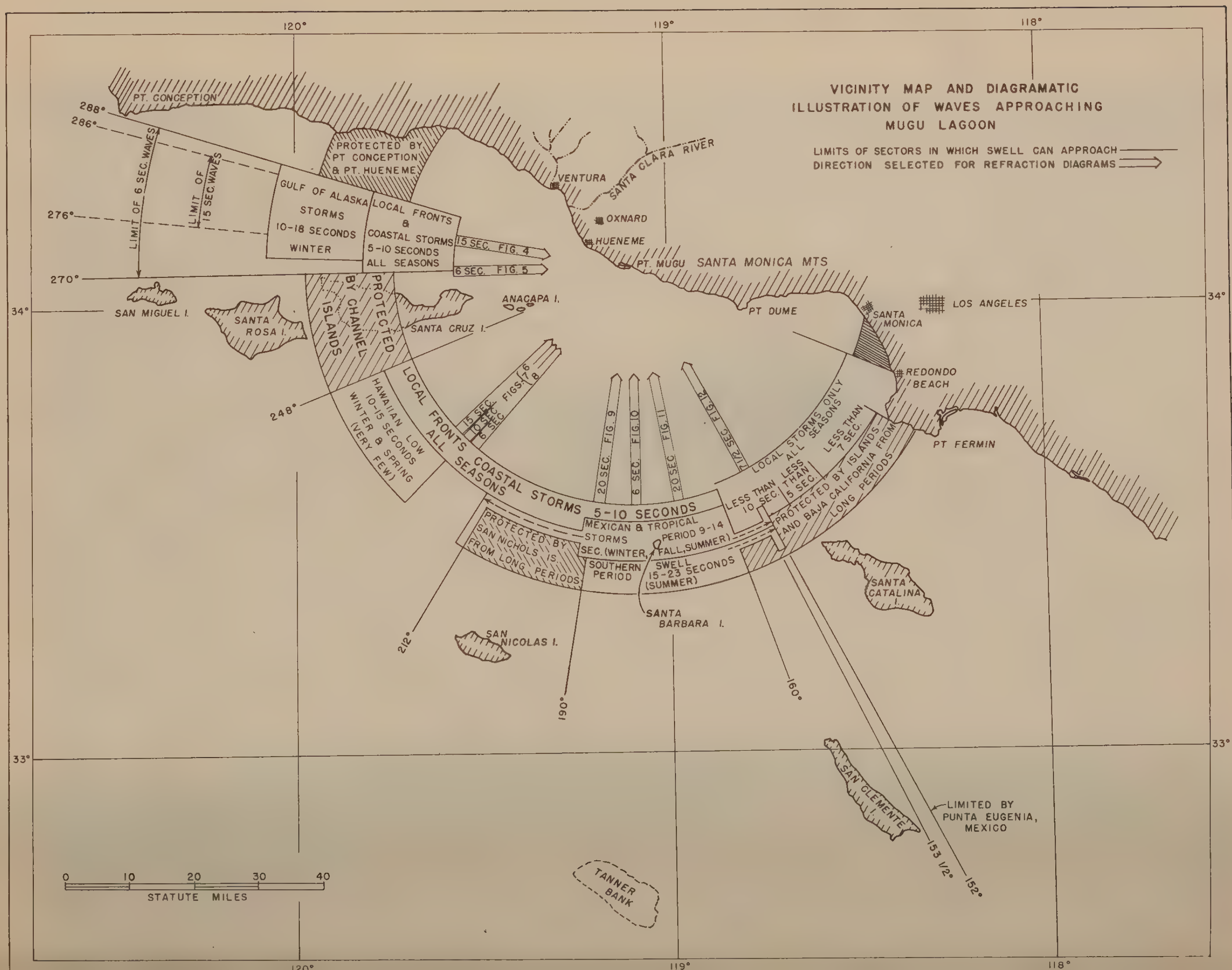
Title and Agency	Survey	Edition	Scale	Contour Interval	Notes
Hydrographic Sheet No. 554, U.S. Coast and Geodetic Survey	1856	1933 (Photostat)	1:20,000* (Photostat)	Soundings in ft. to 18 ft., beyond in fath. below MLLW	Lat. 34°04' - 34°06' Long. 119°02' - 119°08'
Hydrographic Sheet No. 1403, U.S.Coast and Geodetic Survey	1878	1931 (Photostat)	1:40,000* (Photostat)	Soundings in ft. to 18 ft., beyond in fath. below MLLW	Lat.33°58' - 34°06': Long. 119°02'-119°10' Coast line evidently reproduced from 1856 survey.
"Hueneme Quadrangle Calif." U. S. Geological Survey	1901	1904 reprinted 1925	1:62,500	50 feet (above MSL)	Lat. 34°00' - 34°15' Long. 119°00' - 119°15'
Hydrographic Sheet No.5425. "Vicinity of Mugu Lagoon, Santa Barbara Channel, Calif. U.S.Coast & Geodetic Survey	1933	1948 (Bromide)	1:10,000	Soundings in fath. below MLLW	Lat.34°04' - 34°06' Long. 119°02' - 119°09'
"Hueneme Quadrangle, Calif." War Dept., U.S. Army Corps of Engrs.	1901 (revised 1940-41)	1942	1:62,500	50 feet (above MSL)	Lat. 34°00' - 34°15' Long. 119°00' - 119°15'
Santa Cruz Island to Descanso Point. (Shepard & Emery, GSA Sp. Paper 31, 1941, Chart I)	All available date up to 1941	1941	1:500,000	300 feet (below MLLW)	
"Hueneme Quadrangle, Calif." War Dept. U.S. Army Corps of Engrs. Sheet 2152 11	1901 (revised 1940-41, 1943)	1947	1:50,000	50 feet (above MSL)	Lat.34°00' - 34°15' Long.119°00' - 119°15' (Shore line features at Mugu reproduced from 1942 edition)

*Scale of original 1:10,000



OXNARD PLAIN WITH MUGU LAGOON IN THE FOREGROUND AND PORT HUENEME IN THE CENTER BACKGROUND. LOOKING APPROXIMATELY WNW, 4 MARCH 1947. (PHOTO BY U.S. NAVY)

FIGURE I



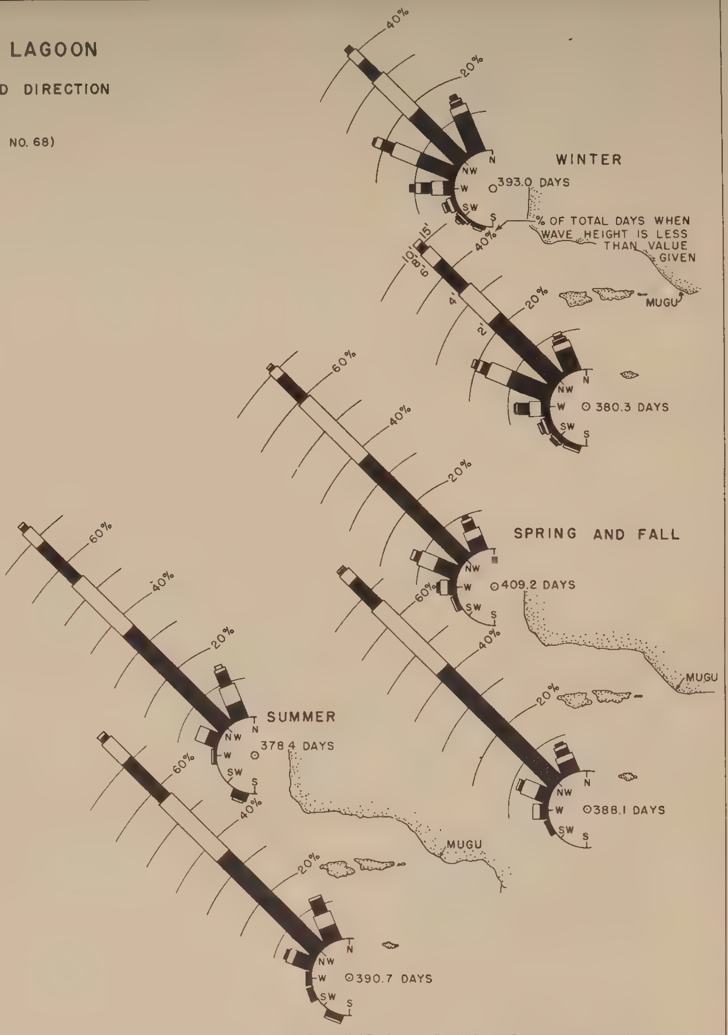
VICINITY MAP AND DIAGRAMATIC ILLUSTRATION OF WAVES APPROACHING MUGU LAGOON

LIMITS OF SECTORS IN WHICH SWELL CAN APPROACH
DIRECTION SELECTED FOR REFRACTION DIAGRAMS
120°
119°
118°
34°
33°
PT. CONCEPTION
288°
286°
276°
270°
LIMIT OF 6 SEC. WAVES
LIMIT OF 15 SEC. WAVES
PROTECTED BY PT CONCEPTION & PT. HUENEME
GULF OF ALASKA STORMS 10-18 SECONDS WINTER
LOCAL FRONTS & COASTAL STORMS 5-10 SECONDS ALL SEASONS
15 SEC. FIG. 4
6 SEC. FIG. 5
VENTURA
SANTA CLARA RIVER
OXNARD
HUENEME
PT. MUGU
SANTA MONICA MTS
PT DUME
SANTA MONICA
LOS ANGELES
REDONDO BEACH
PT FERMIN
SAN MIGUEL I.
SANTA ROSA I.
SANTA CRUZ I.
ANACAPA I.
PROTECTED BY CHANNEL ISLANDS
248°
HAWAIIAN LOW 10-15 SECONDS WINTER & SPRING (VERY FEW)
LOCAL FRONTS ALL SEASONS
COASTAL STORMS 5-10 SECONDS
15 SEC. 10 SEC. 6 SEC.
FIGS. 6 7 8
20 SEC. FIG. 9
6 SEC. FIG. 10
20 SEC. FIG. 11
7 1/2 SEC. FIG. 12
LOCAL STORMS ONLY ALL SEASONS
LESS THAN 7 SEC.
LESS THAN 5 SEC.
LESS THAN 10 SEC.
PROTECTED BY ISLANDS AND BAJA CALIFORNIA FROM LONG PERIODS
MEXICAN & TROPICAL STORMS PERIOD 9-14 SEC. (WINTER, FALL, SUMMER)
PROTECTED BY SAN NICHOLS IS FROM LONG PERIODS
SOUTHERN PERIOD
SWELL 15-23 SECONDS (SUMMER)
212°
190°
160°
SAN NICOLAS I.
SANTA BARBARA I.
SANTA CATALINA I.
SAN CLEMENTE I.
LIMITED BY PUNTA EUGENIA, MEXICO
153 1/2°
152°
TANNER BANK
0
10
20
30
40
STATUTE MILES

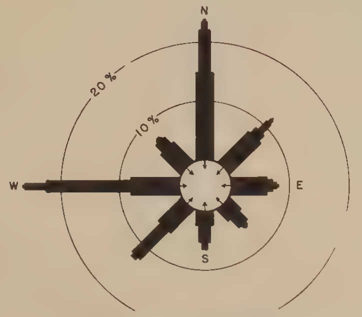
VICINITY OF MUGU LAGOON

SEASONAL WAVE HEIGHT AND DIRECTION ROSES

(FROM S.I.O. WAVE REPORT NO. 68)



NOTE: WAVE ROSES DO NOT INCLUDE SWELL FROM MEXICAN AND TROPICAL STORMS OR FROM SOUTHERN HEMISPHERE.



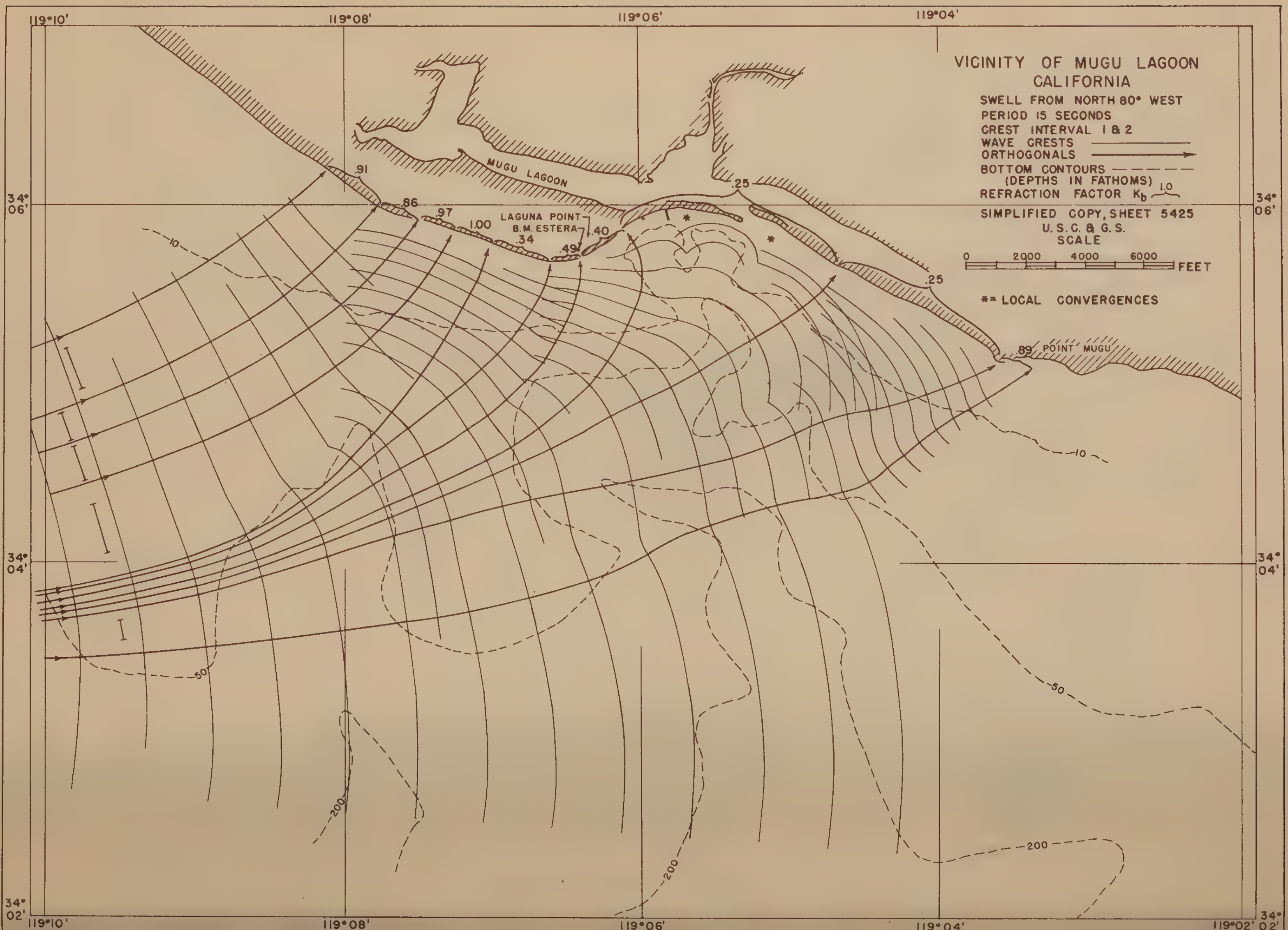
ANNUAL WIND ROSE

BY DIRECTIONS AND SPEED GROUPS. VECTOR MAGNITUDES INDICATE PERCENT OF TIME AT EACH VELOCITY AND FROM EACH DIRECTION (FROM ANNUAL WIND DATA, MUGU AIR STRIP, 1948)

LEGEND

0-5 KNOTS
5-10
10-20
20-30
30+

FIGURE 3


VICINITY OF MUGU LAGOON
CALIFORNIA
SWELL FROM NORTH 80° WEST
PERIOD 15 SECONDS
CREST INTERVAL 1 & 2
WAVE CRESTS
ORTHOGONALS
BOTTOM CONTOURS
(DEPTHS IN FATHOMS)
REFRACTION FACTOR K_b 1.0
SIMPLIFIED COPY, SHEET 5425
U.S.C. & G.S.
SCALE
0 2000 4000 6000 FEET
* = LOCAL CONVERGENCES
MUGU LAGOON
LAGUNA POINT
B.M. ESTERA
POINT MUGU
.91
.86
.97
1.00
.34
.49
.40
.25
.25
.89
10
10
50
50
200
200
200
119°10'
119°08'
119°06'
119°04'
119°02'
34° 06'
34° 04'
34° 02'

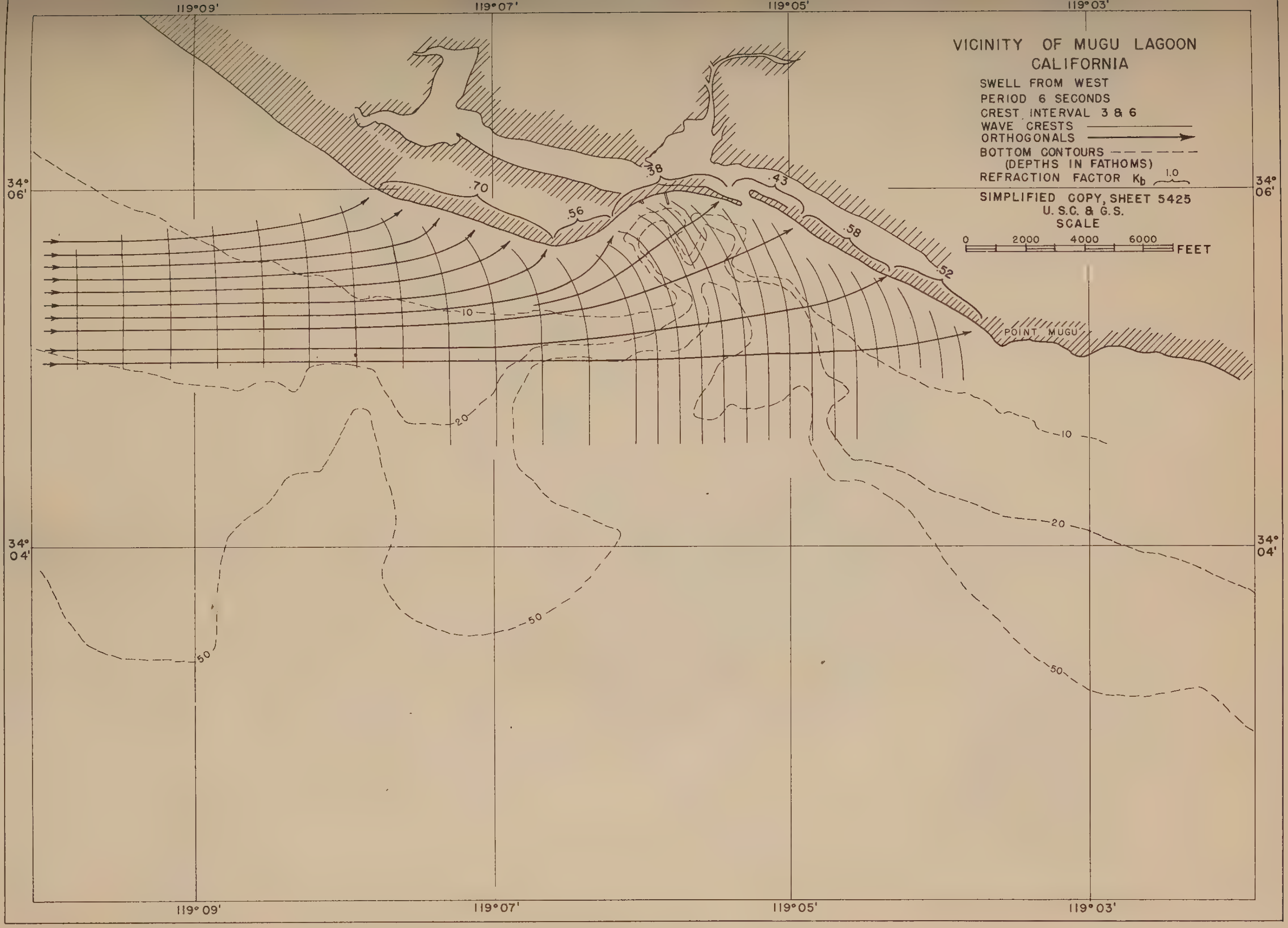
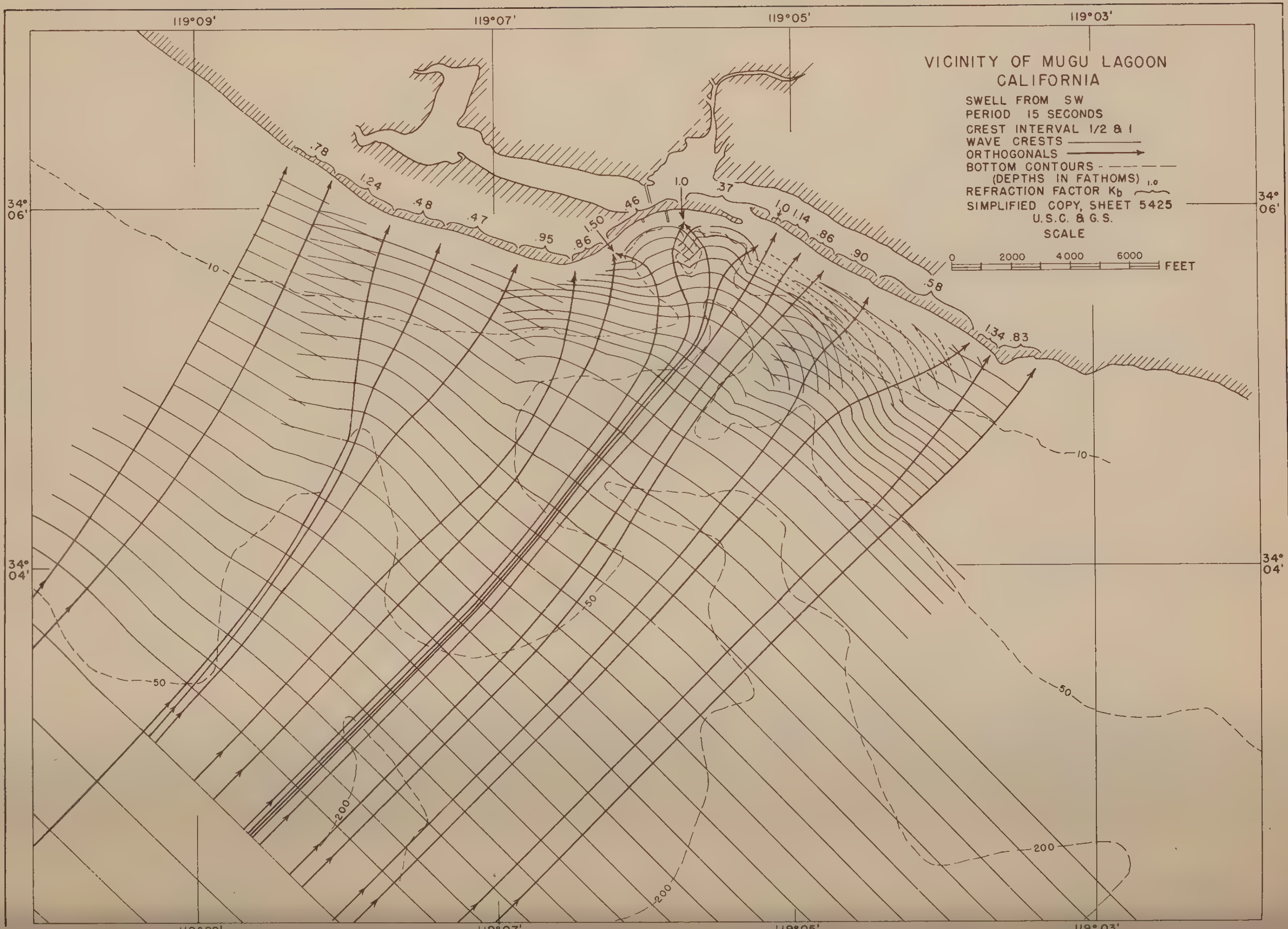

VICINITY OF MUGU LAGOON
CALIFORNIA
SWELL FROM WEST
PERIOD 6 SECONDS
CREST INTERVAL 3 & 6
WAVE CRESTS
ORTHOGONALS
BOTTOM CONTOURS
(DEPTHS IN FATHOMS)
REFRACTION FACTOR K_b
1.0
SIMPLIFIED COPY, SHEET 5425
U.S.C. & G.S.
SCALE
0
2000
4000
6000
FEET
119°09'
119°07'
119°05'
119°03'
34° 06'
34° 04'
POINT MUGU
.70
.56
.38
.43
.58
.52
10
20
50

FIGURE 5


VICINITY OF MUGU LAGOON
CALIFORNIA
SWELL FROM SW
PERIOD 15 SECONDS
CREST INTERVAL 1/2 & 1
WAVE CRESTS
ORTHOGONALS
BOTTOM CONTOURS
(DEPTHS IN FATHOMS)
1.0
REFRACTION FACTOR Kb
SIMPLIFIED COPY, SHEET 5425
U.S.C. & G.S.
SCALE
0
2000
4000
6000
FEET
119°09'
119°07'
119°05'
119°03'
34° 06'
34° 04'
.78
1.24
.48
.47
.95
.86
1.50
.46
1.0
.37
1.0
1.14
.86
.90
.58
1.34
.83
10
50
200

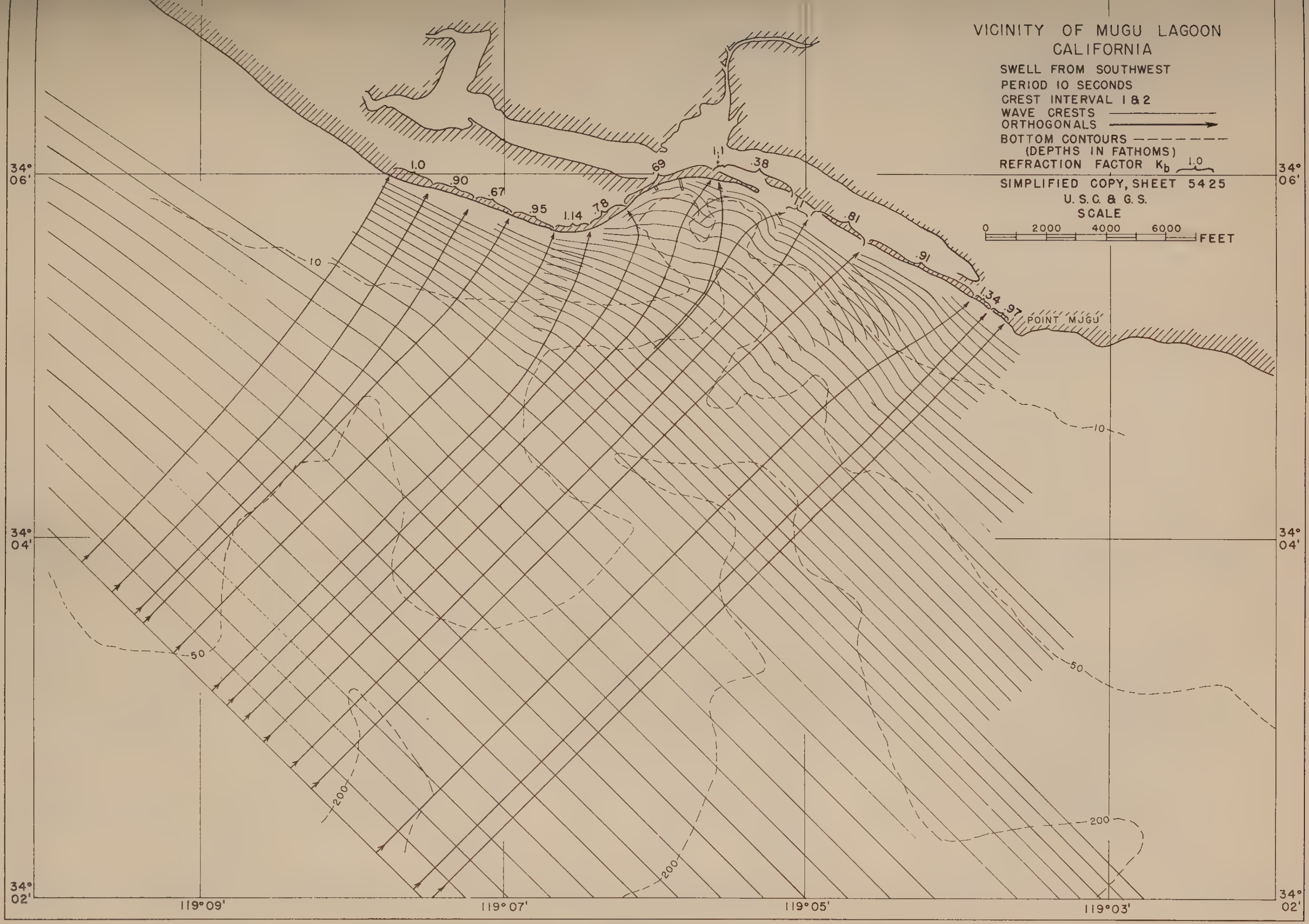
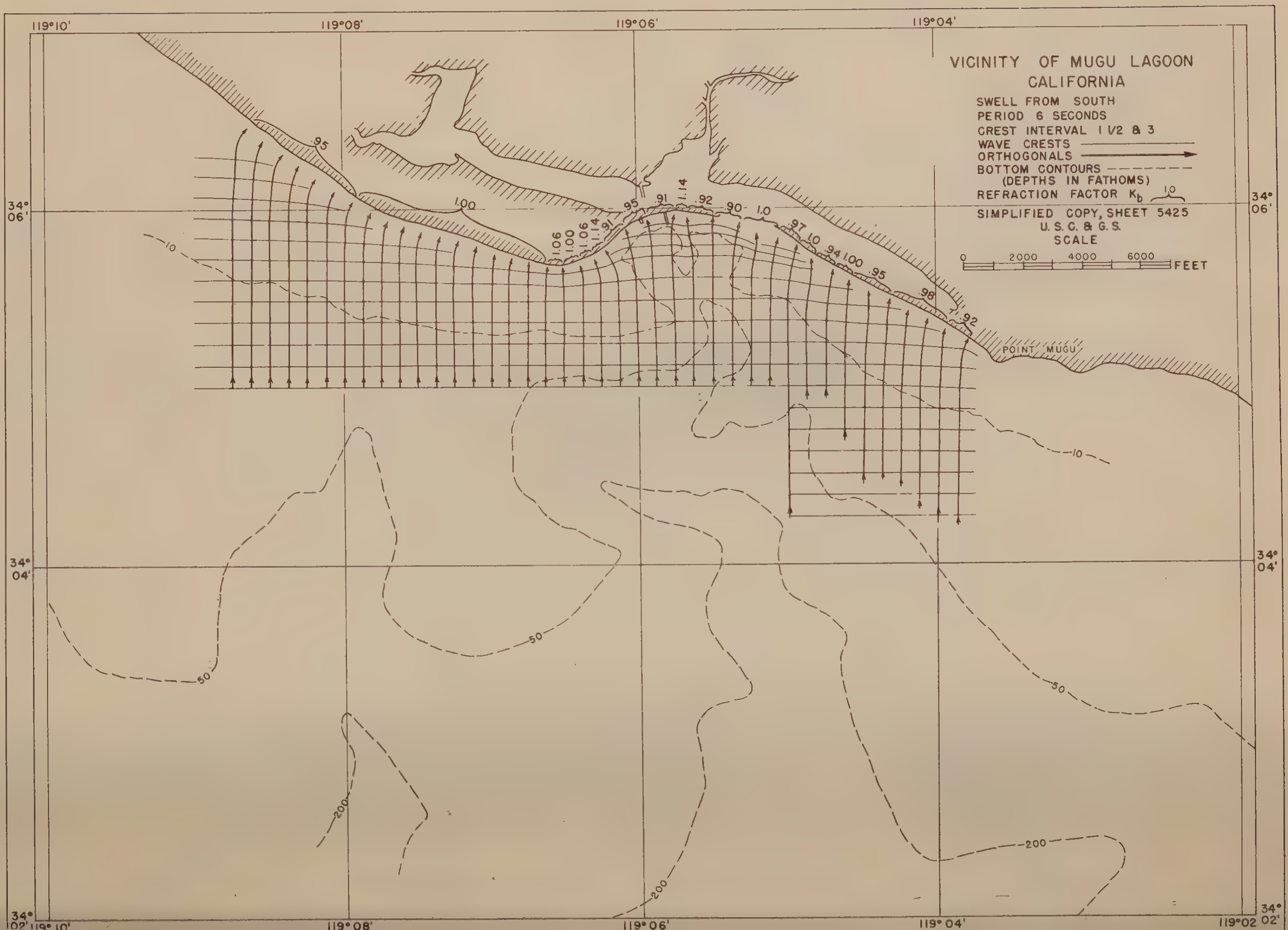

VICINITY OF MUGU LAGOON
CALIFORNIA
SWELL FROM SOUTHWEST
PERIOD 10 SECONDS
CREST INTERVAL 1 & 2
WAVE CRESTS
ORTHOGONALS
BOTTOM CONTOURS
(DEPTHS IN FATHOMS)
REFRACTION FACTOR K_b 1.0
SIMPLIFIED COPY, SHEET 5425
U. S. C. & G. S.
SCALE
0 2000 4000 6000 FEET
POINT MUGU
1.0
.90
.67
.95
1.14
.78
.69
1.1
.38
1.1
.81
.91
1.34
.97
10
10
50
50
200
200
200
34° 06'
34° 04'
34° 02'
119° 09'
119° 07'
119° 05'
119° 03'

FIGURE 7


VICINITY OF MUGU LAGOON
CALIFORNIA
SWELL FROM SOUTH
PERIOD 6 SECONDS
CREST INTERVAL 1 1/2 & 3
WAVE CRESTS
ORTHOGONALS
BOTTOM CONTOURS
(DEPTHS IN FATHOMS)
REFRACTION FACTOR K_b 1.0
SIMPLIFIED COPY, SHEET 5425
U. S. C. & G. S.
SCALE
0 2000 4000 6000 FEET
POINT MUGU
119°10'
119°08'
119°06'
119°04'
119°02'
34° 06'
34° 04'
34° 02'
.95
1.00
1.06
1.00
1.06
1.14
.91
.95
.91
1.14
.92
.90
1.0
.97
1.0
.94
1.00
.95
.98
.92
10
50
200

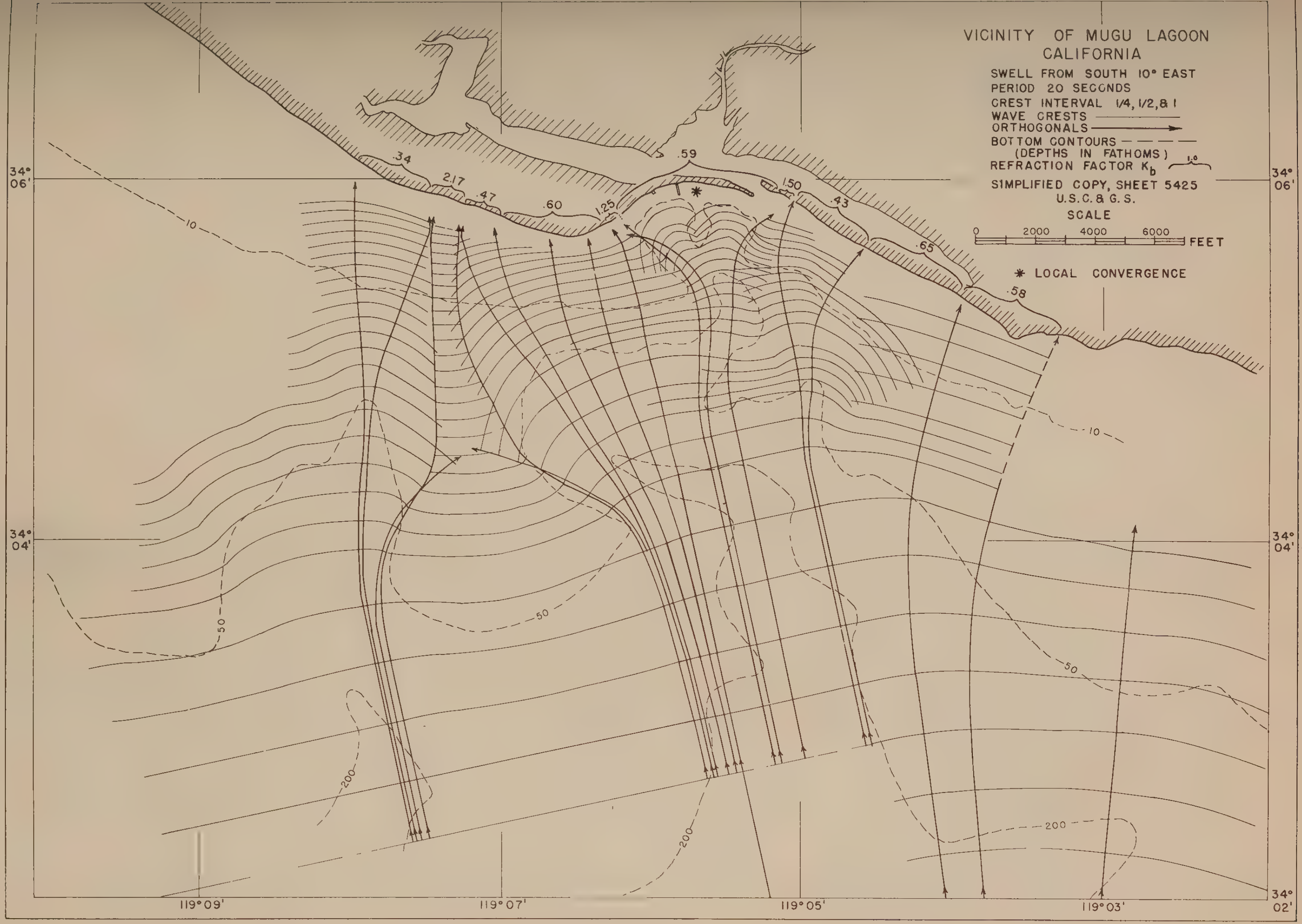
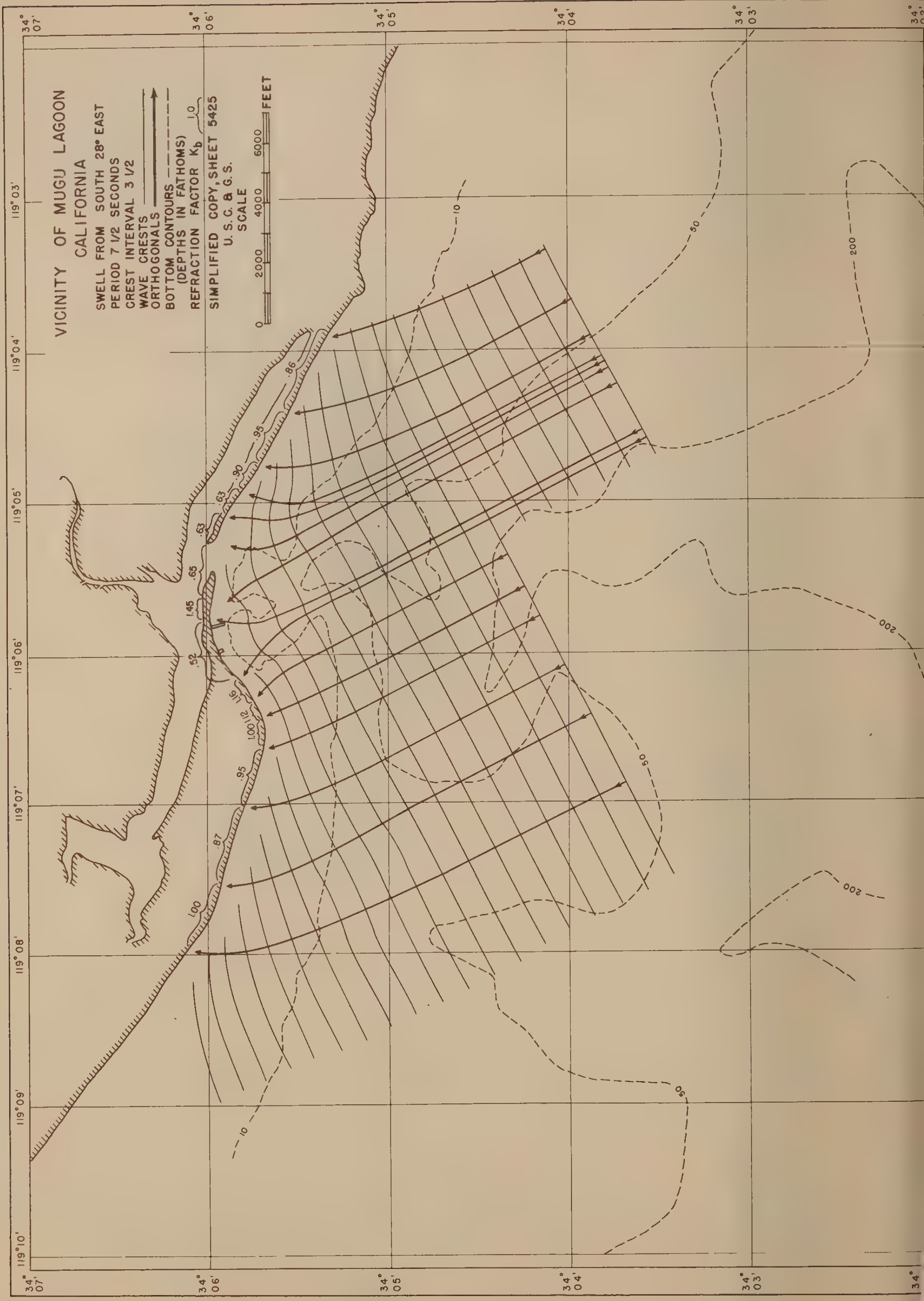

VICINITY OF MUGU LAGOON
CALIFORNIA
SWELL FROM SOUTH 10° EAST
PERIOD 20 SECONDS
CREST INTERVAL 1/4, 1/2, & 1
WAVE CRESTS
ORTHOGONALS
BOTTOM CONTOURS
(DEPTHS IN FATHOMS)
REFRACTION FACTOR K_b
1.0
SIMPLIFIED COPY, SHEET 5425
U.S.C. & G.S.
SCALE
0
2000
4000
6000
FEET
* LOCAL CONVERGENCE
.34
2.17
.47
.60
1.25
.59
1.50
.43
.65
.58
10
50
200
34° 06'
34° 04'
34° 02'
119° 09'
119° 07'
119° 05'
119° 03'

FIGURE 11


VICINITY OF MUGU LAGOON
CALIFORNIA
SWELL FROM SOUTH 28° EAST
PERIOD 7 1/2 SECONDS
CREST INTERVAL 3 1/2
WAVE CRESTS
ORTHOGONALS
BOTTOM CONTOURS
(DEPTHS IN FATHOMS)
REFRACTION FACTOR K_b
1.0
SIMPLIFIED COPY, SHEET 5425
U. S. C. & G. S.
SCALE
0
2000
4000
6000
FEET
34° 07'
34° 06'
34° 05'
34° 04'
34° 03'
119° 03'
119° 04'
119° 05'
119° 06'
119° 07'
119° 08'
119° 09'
119° 10'
10
50
200
.86
.95
.90
.63
.63
.65
1.45
.52
.91
1.12
1.00
.95
.87
1.00

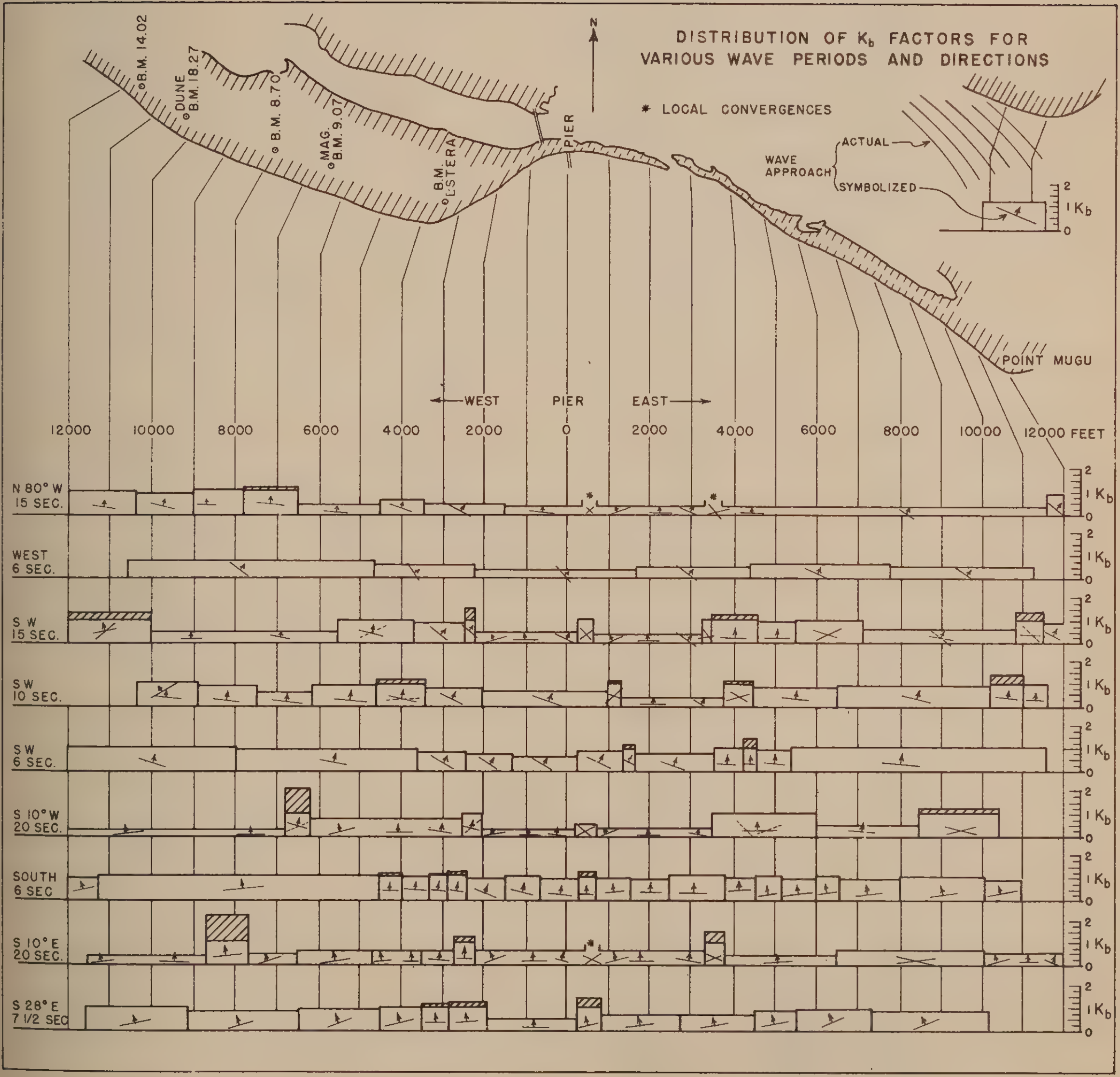

DISTRIBUTION OF K_b FACTORS FOR VARIOUS WAVE PERIODS AND DIRECTIONS
N
* LOCAL CONVERGENCES
WAVE APPROACH
ACTUAL
SYMBOLIZED
2
1 K_b
0
B.M. 14.02
DUNE B.M. 18.27
B.M. 8.70
MAG. B.M. 9.07
B.M. L'STERA
PIER
POINT MUGU
WEST
PIER
EAST
12000
10000
8000
6000
4000
2000
0
2000
4000
6000
8000
10000
12000 FEET
N 80° W 15 SEC.
WEST 6 SEC.
S W 15 SEC.
S W 10 SEC.
S W 6 SEC.
S 10° W 20 SEC.
SOUTH 6 SEC.
S 10° E 20 SEC.
S 28° E 7 1/2 SEC.

FIGURE 13

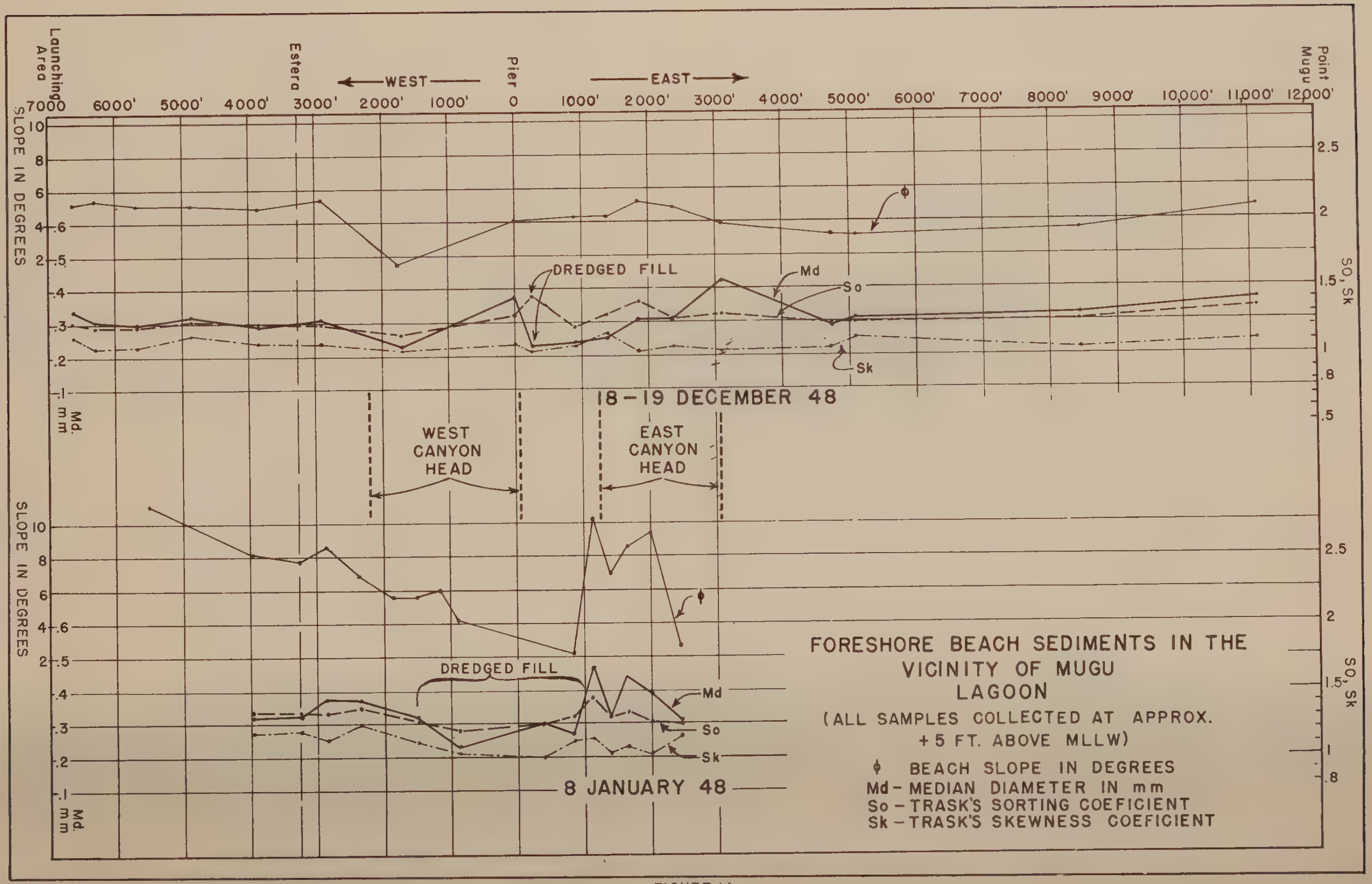
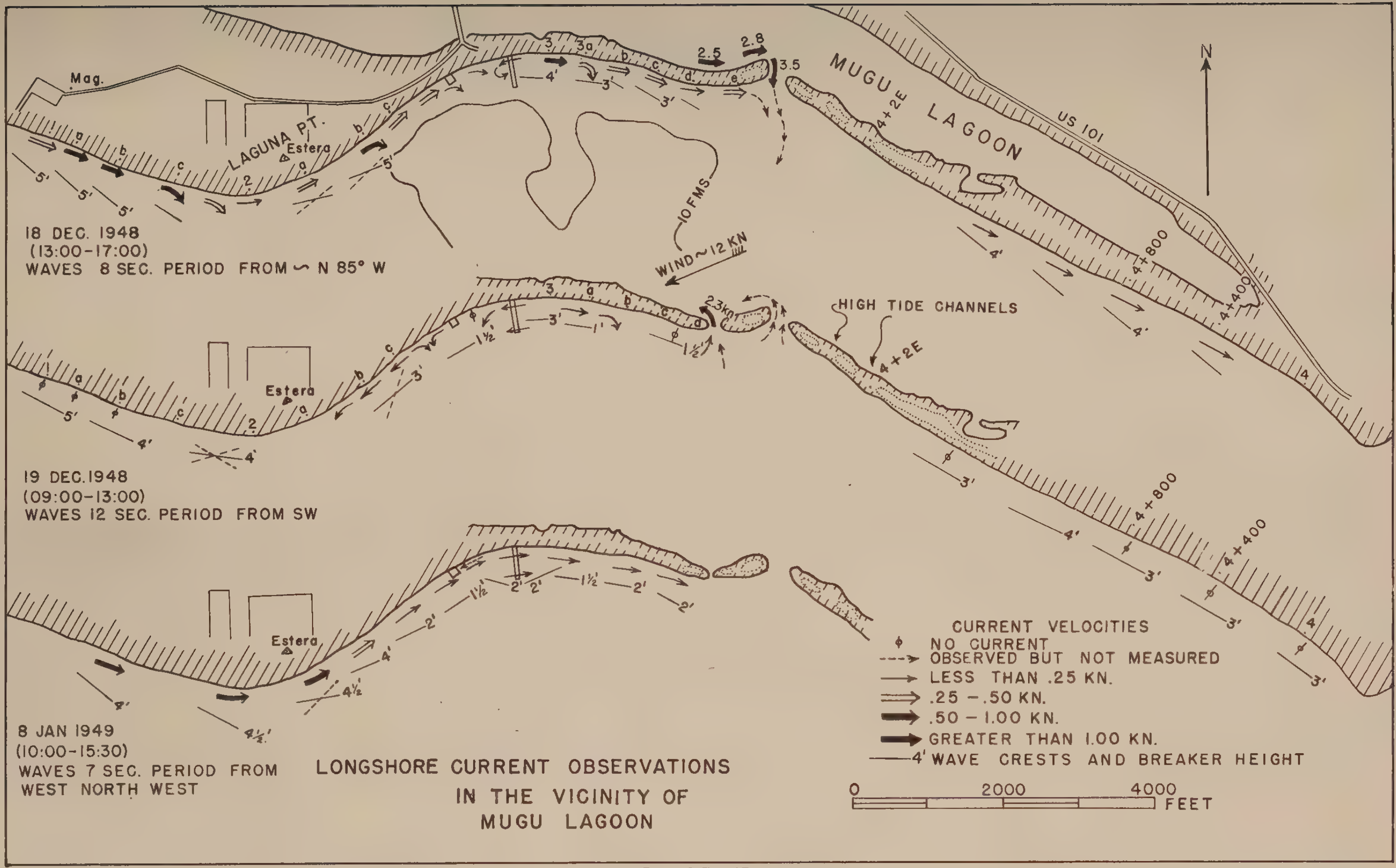

FORESHORE BEACH SEDIMENTS IN THE VICINITY OF MUGU LAGOON
(ALL SAMPLES COLLECTED AT APPROX. +5 FT. ABOVE MLLW)
ϕ BEACH SLOPE IN DEGREES
Md - MEDIAN DIAMETER IN mm
So - TRASK'S SORTING COEFICIENT
Sk - TRASK'S SKEWNESS COEFICIENT
Launching Area
Estera
Pier
Point Mugu
WEST
EAST
7000
6000'
5000'
4000'
3000'
2000'
1000'
0
1000'
2000'
3000'
4000'
5000'
6000'
7000'
8000'
9000'
10,000'
11,000'
12,000'
SLOPE IN DEGREES
10
8
6
4
2
.6
.5
.4
.3
.2
.1
Md. mm
SO, Sk
2.5
2
1.5
1
.8
.5
DREDGED FILL
Md
So
Sk
ϕ
18-19 DECEMBER 48
WEST CANYON HEAD
EAST CANYON HEAD
8 JANUARY 48

FIGURE 14


MUGU LAGOON
US 101
N
Mag.
LAGUNA PT.
Estera
10 FMS
WIND ~ 12 KN
HIGH TIDE CHANNELS
4+2E
4+800
4+400
2.5
2.8
3.5
2.3kn
CURRENT VELOCITIES
NO CURRENT
OBSERVED BUT NOT MEASURED
LESS THAN .25 KN.
.25 – .50 KN.
.50 – 1.00 KN.
GREATER THAN 1.00 KN.
4' WAVE CRESTS AND BREAKER HEIGHT
0
2000
4000
FEET

18 DEC. 1948
(13:00-17:00)
WAVES 8 SEC. PERIOD FROM ∽ N 85° W

19 DEC. 1948
(09:00-13:00)
WAVES 12 SEC. PERIOD FROM SW

8 JAN 1949
(10:00-15:30)
WAVES 7 SEC. PERIOD FROM
WEST NORTH WEST

LONGSHORE CURRENT OBSERVATIONS
IN THE VICINITY OF
MUGU LAGOON

FIGURE 15

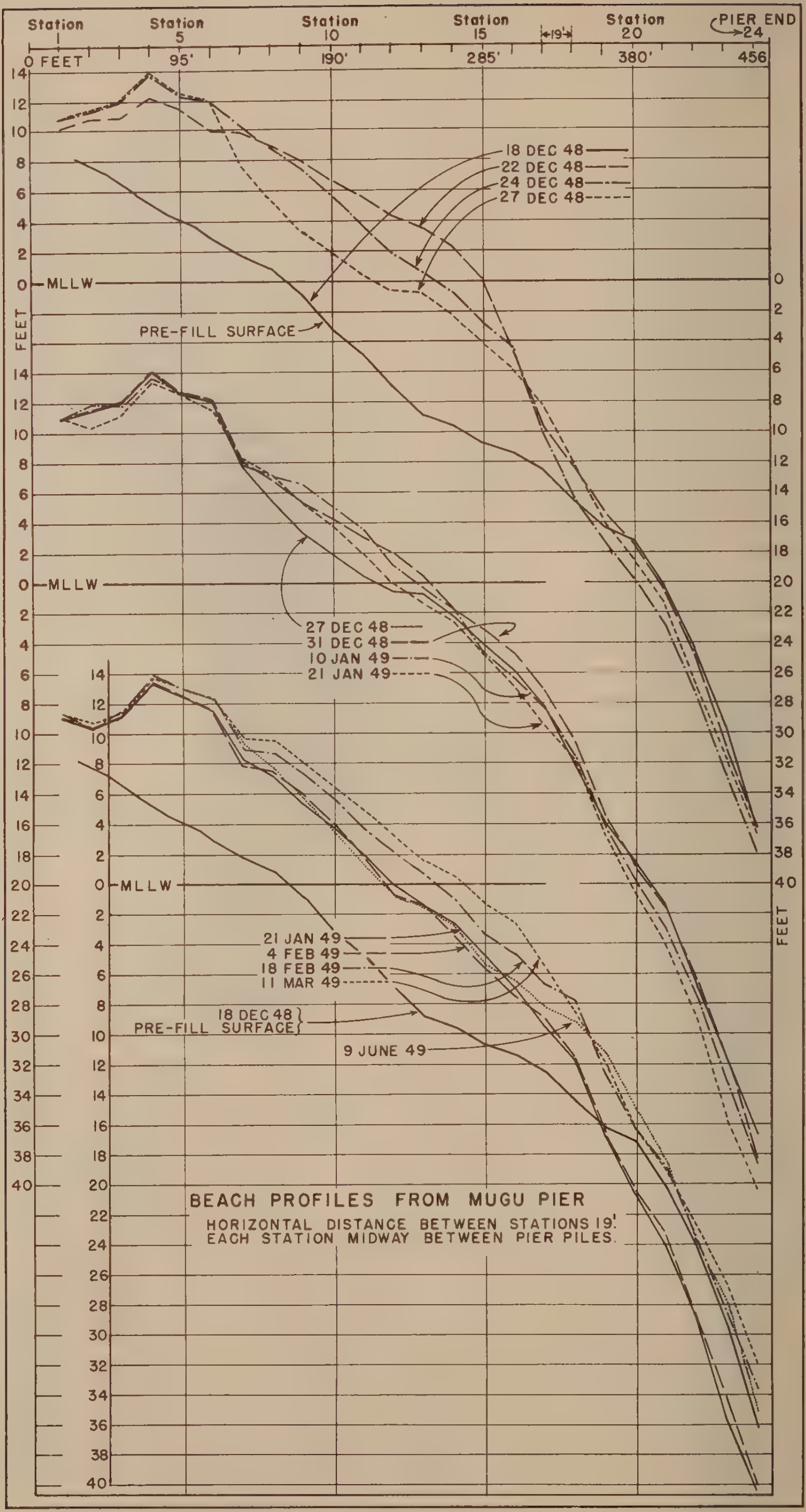
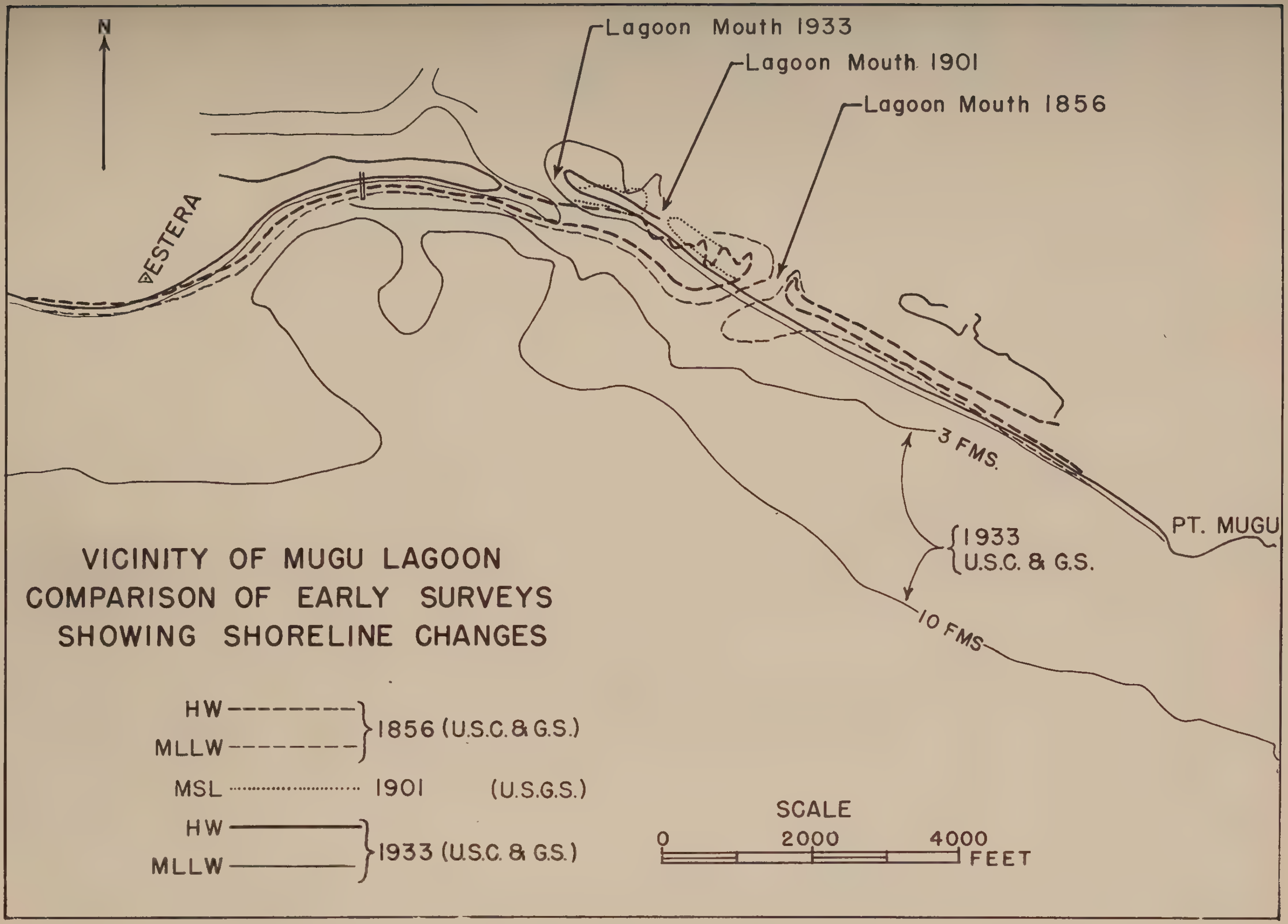
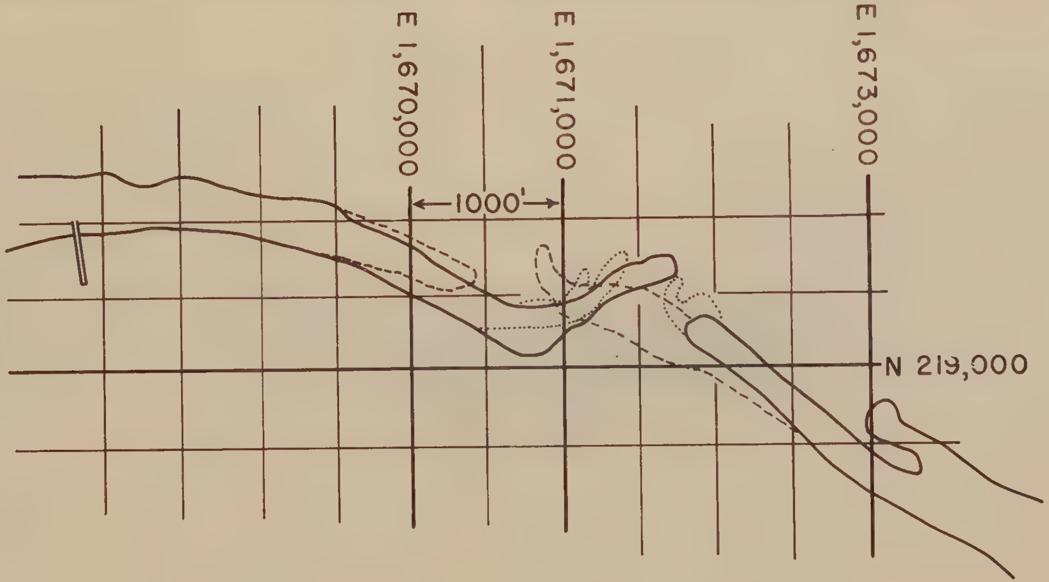

Station 1
Station 5
Station 10
Station 15
Station 20
PIER END 24
19'
0 FEET
95'
190'
285'
380'
456
MLLW
FEET
PRE-FILL SURFACE
18 DEC 48
22 DEC 48
24 DEC 48
27 DEC 48
27 DEC 48
31 DEC 48
10 JAN 49
21 JAN 49
21 JAN 49
4 FEB 49
18 FEB 49
11 MAR 49
18 DEC 48
PRE-FILL SURFACE
9 JUNE 49
14
12
10
8
6
4
2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
BEACH PROFILES FROM MUGU PIER
HORIZONTAL DISTANCE BETWEEN STATIONS 19'.
EACH STATION MIDWAY BETWEEN PIER PILES.

FIGURE 16


N
Lagoon Mouth 1933
Lagoon Mouth 1901
Lagoon Mouth 1856
ESTERA
3 FMS.
10 FMS.
1933 U.S.C. & G.S.
PT. MUGU
HW, MLLW 1856 (U.S.C. & G.S.)
MSL 1901 (U.S.G.S.)
HW, MLLW 1933 (U.S.C. & G.S.)
SCALE
0
2000
4000
FEET

VICINITY OF MUGU LAGOON
COMPARISON OF EARLY SURVEYS
SHOWING SHORELINE CHANGES

FIGURE 17


E 1,670,000
E 1,671,000
E 1,673,000
1000'
N 219,000

COMPARISON OF AERIAL PHOTOGRAPHS SHOWING CHANGES IN THE MUGU SAND SPITS

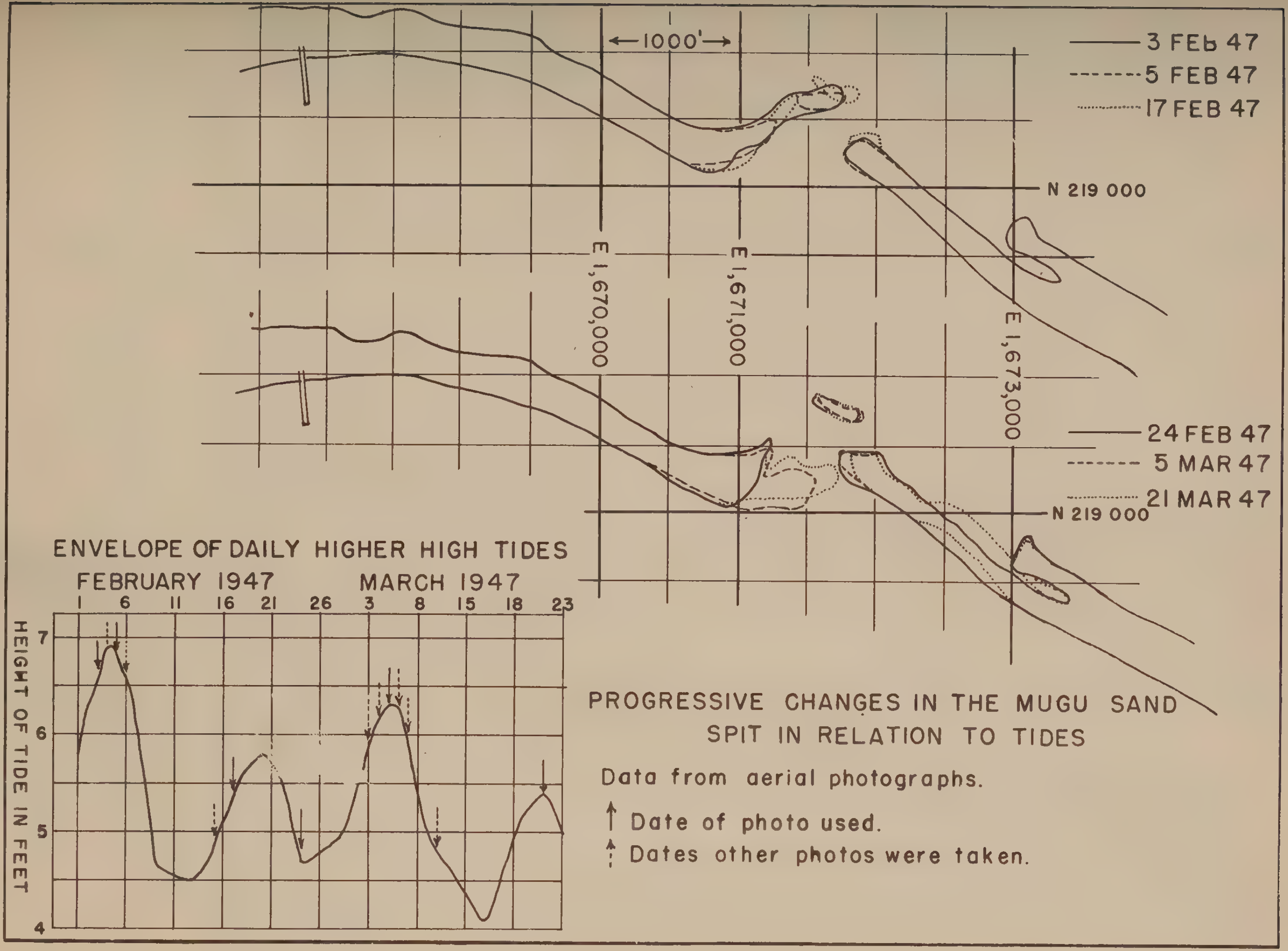
--------- 4 MAR. 1945

.... 9 NOV. 1946

——— 3 FEB 1947

(SEE ALSO FIGURES 19 & 20)

FIGURE 18


3 FEb 47
5 FEB 47
17 FEB 47
24 FEB 47
5 MAR 47
21 MAR 47
1000'
N 219 000
N 219 000
E 1,670,000
E 1,671,000
E 1,673,000
ENVELOPE OF DAILY HIGHER HIGH TIDES
FEBRUARY 1947
MARCH 1947
1
6
11
16
21
26
3
8
15
18
23
7
6
5
4
HEIGHT OF TIDE IN FEET

PROGRESSIVE CHANGES IN THE MUGU SAND SPIT IN RELATION TO TIDES

Data from aerial photographs.

↑ Date of photo used.

⇡ Dates other photos were taken.

FIGURE 19

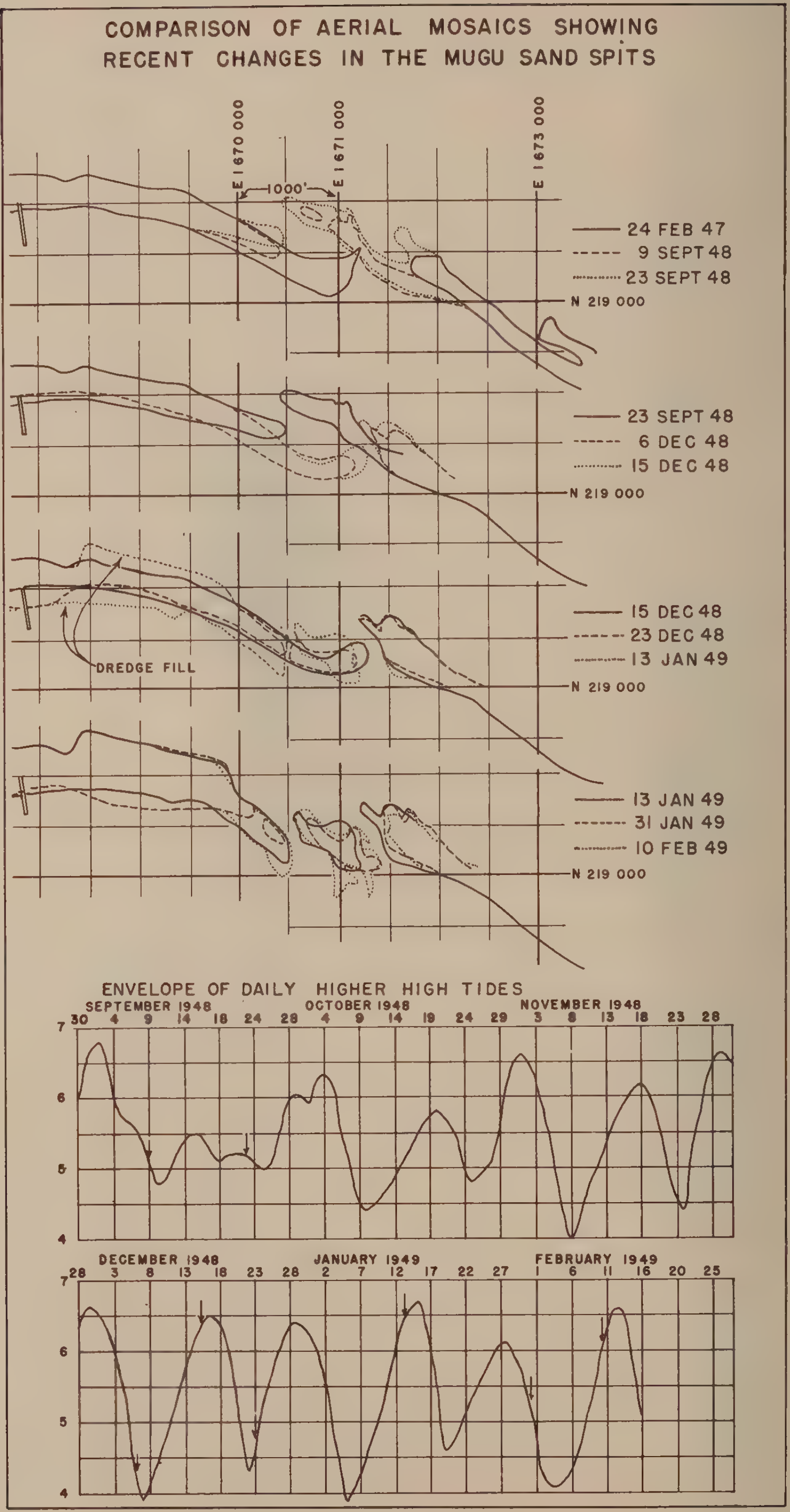
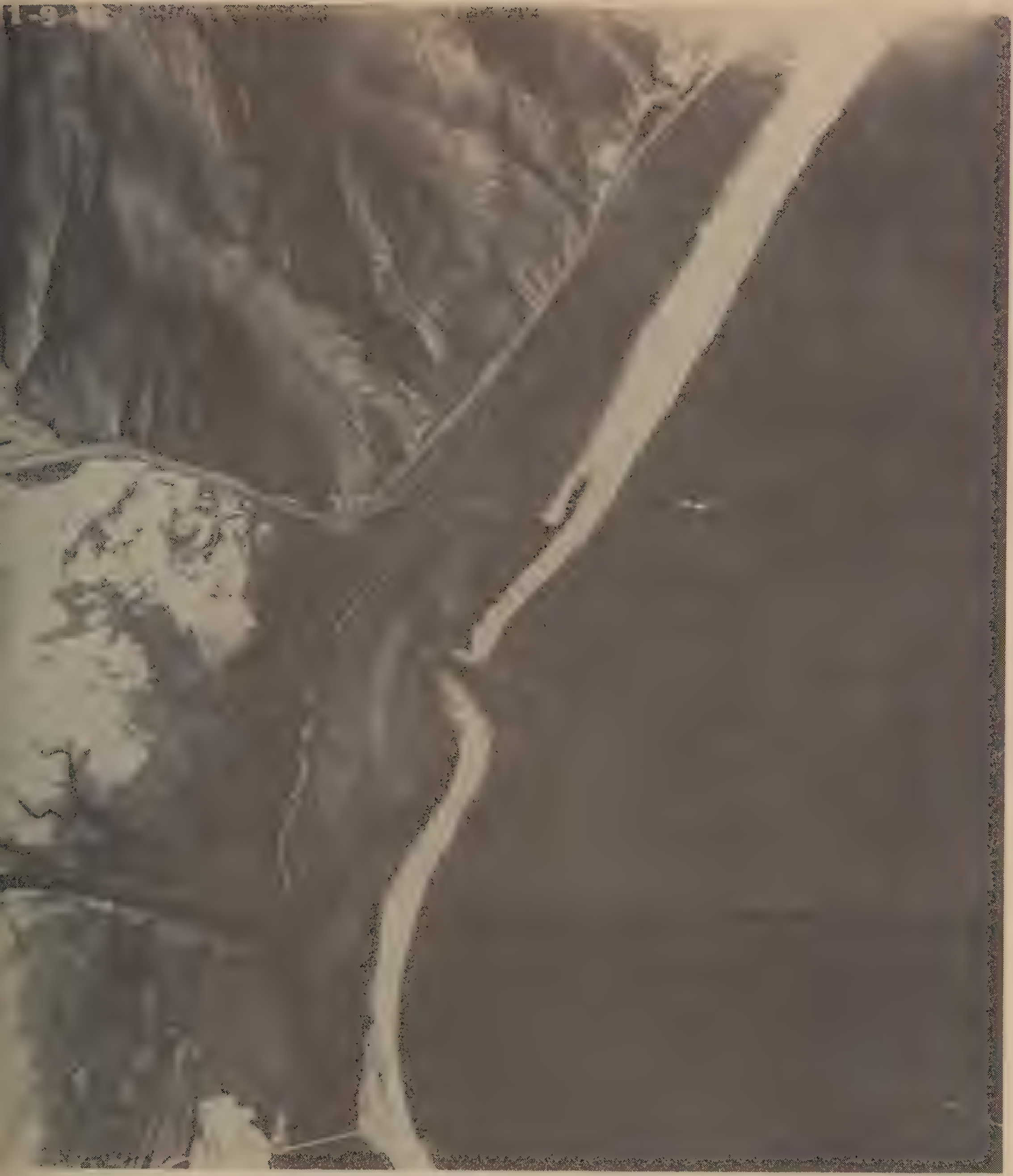
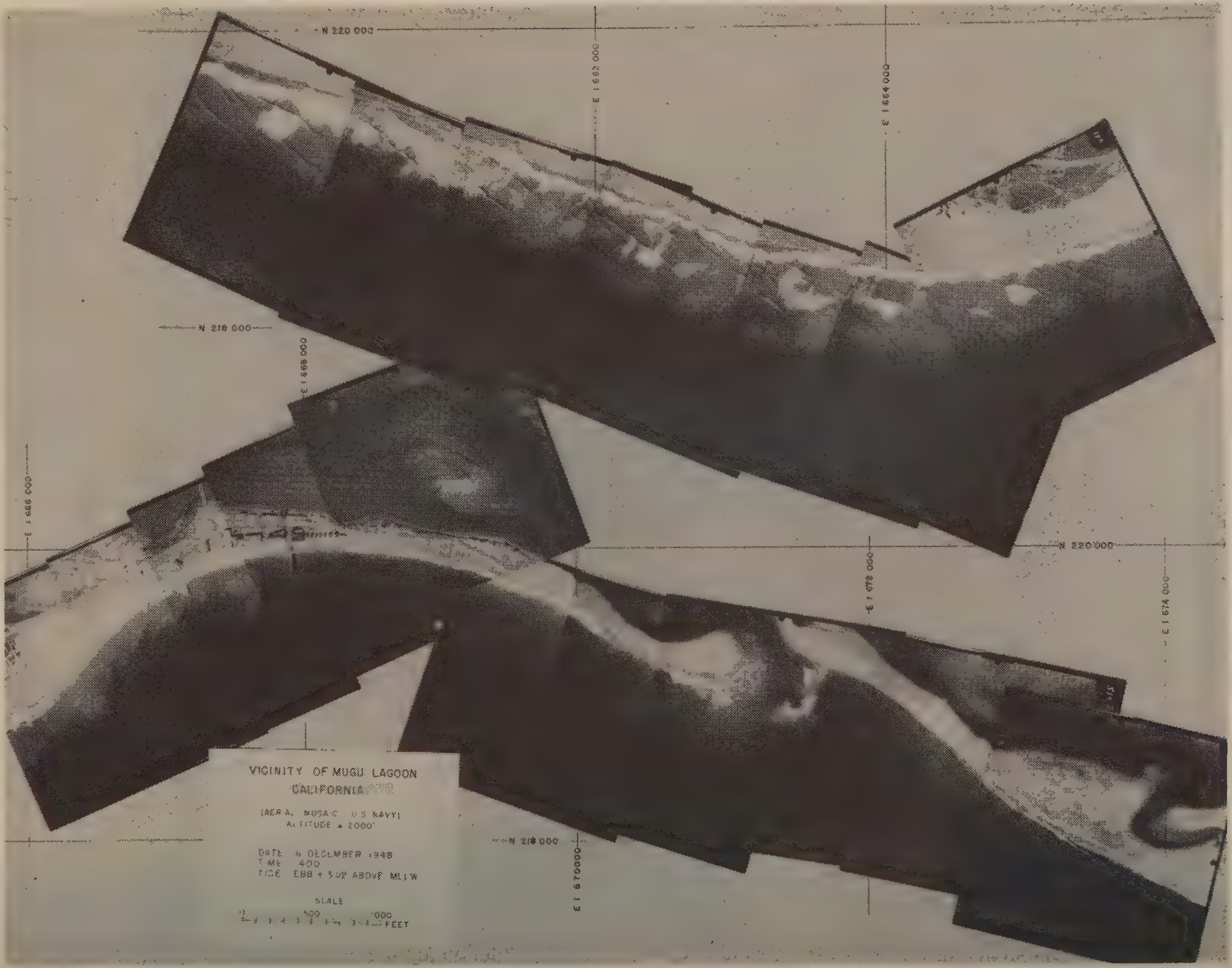

COMPARISON OF AERIAL MOSAICS SHOWING RECENT CHANGES IN THE MUGU SAND SPITS
E 1670 000
E 1671 000
E 1673 000
1000'
24 FEB 47
9 SEPT 48
23 SEPT 48
N 219 000
23 SEPT 48
6 DEC 48
15 DEC 48
N 219 000
15 DEC 48
23 DEC 48
13 JAN 49
DREDGE FILL
N 219 000
13 JAN 49
31 JAN 49
10 FEB 49
N 219 000
ENVELOPE OF DAILY HIGHER HIGH TIDES
SEPTEMBER 1948
OCTOBER 1948
NOVEMBER 1948
30 4 9 14 18 24 28 4 9 14 19 24 29 3 8 13 18 23 28
7
6
5
4
DECEMBER 1948
JANUARY 1949
FEBRUARY 1949
28 3 8 13 18 23 28 2 7 12 17 22 27 1 6 11 16 20 25
7
6
5
4

FIGURE 20

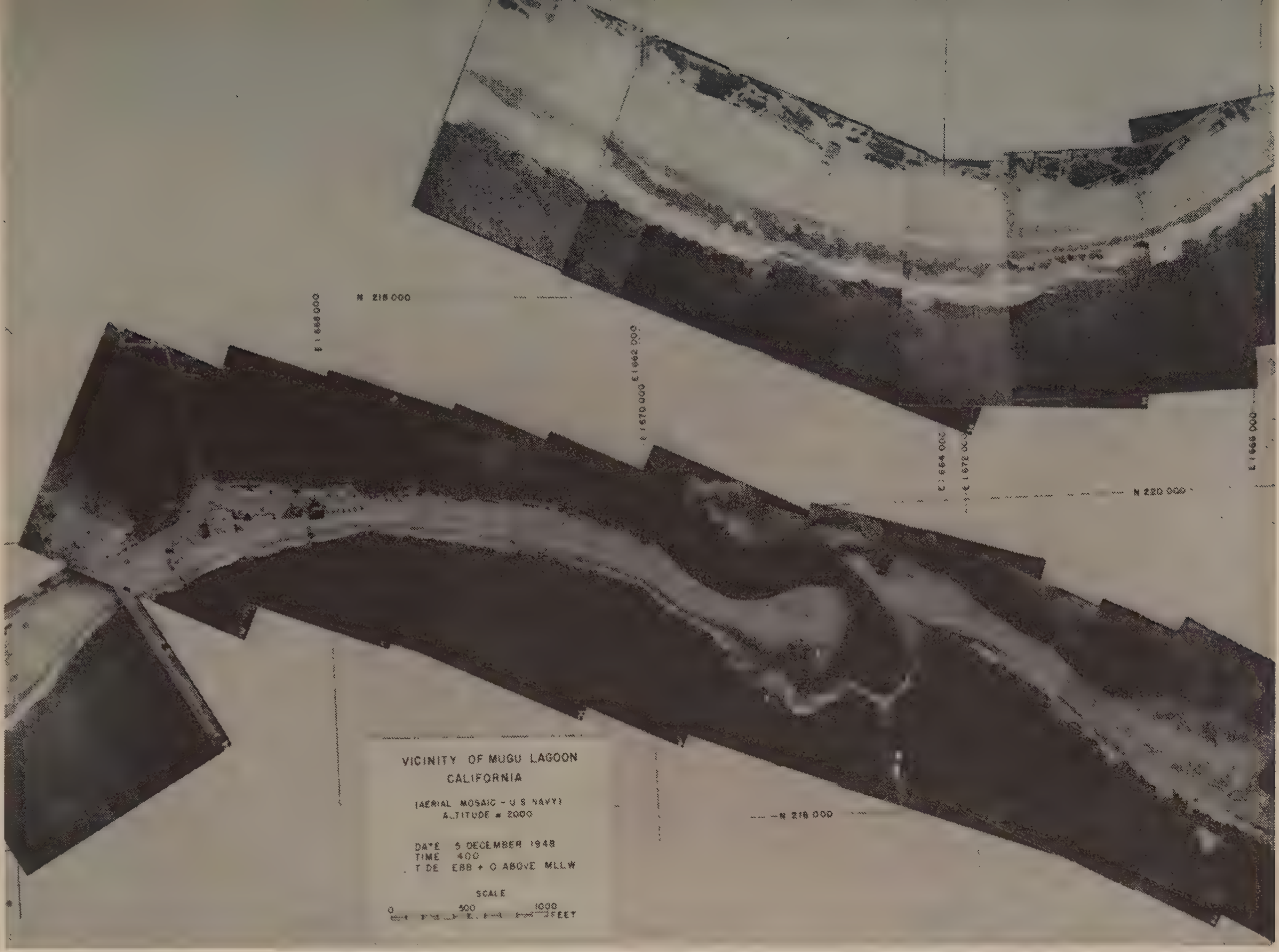


VICINITY OF MUGU LAGOON SHOWING DEVELOPMENT OF A COMPOUND RECURVED SPIT FOLLOWING A NEAP TIDE PERIOD. 9 NOVEMBER 1946 (PHOTO BY FAIRCHILD AERIAL SURVEY)

FIGURE 21


N 220 000
N 218 000
E 1 662 000
E 1 664 000
E 1 666 000
E 1 668 000
E 1 670000
E 1 672 000
E 1 674 000
VICINITY OF MUGU LAGOON
CALIFORNIA
(AERIAL MOSAIC U S NAVY)
ALTITUDE = 2000'
DATE 6 DECEMBER 1948
TIME 400
TIDE EBB + 3.2 ABOVE MLLW
SCALE
0 500 1000
FEET

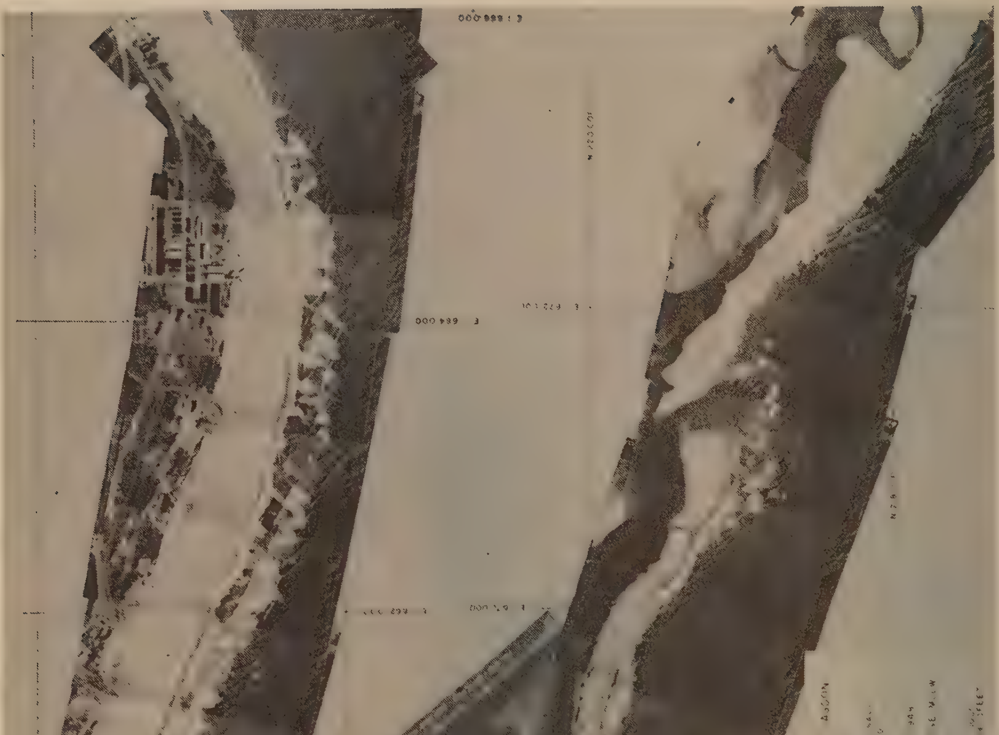
MUGU BEACH AND SAND SPITS ON 6 DECEMBER 1948. NOTE DIAGONAL WAVE APPROACH ON THE BEACH WEST OF MUGU PIER (UPPER STRIP OF PHOTOGRAPHS). THE CALIFORNIA LAMBERT ZONE 5 GRID SYSTEM IS SHOWN.



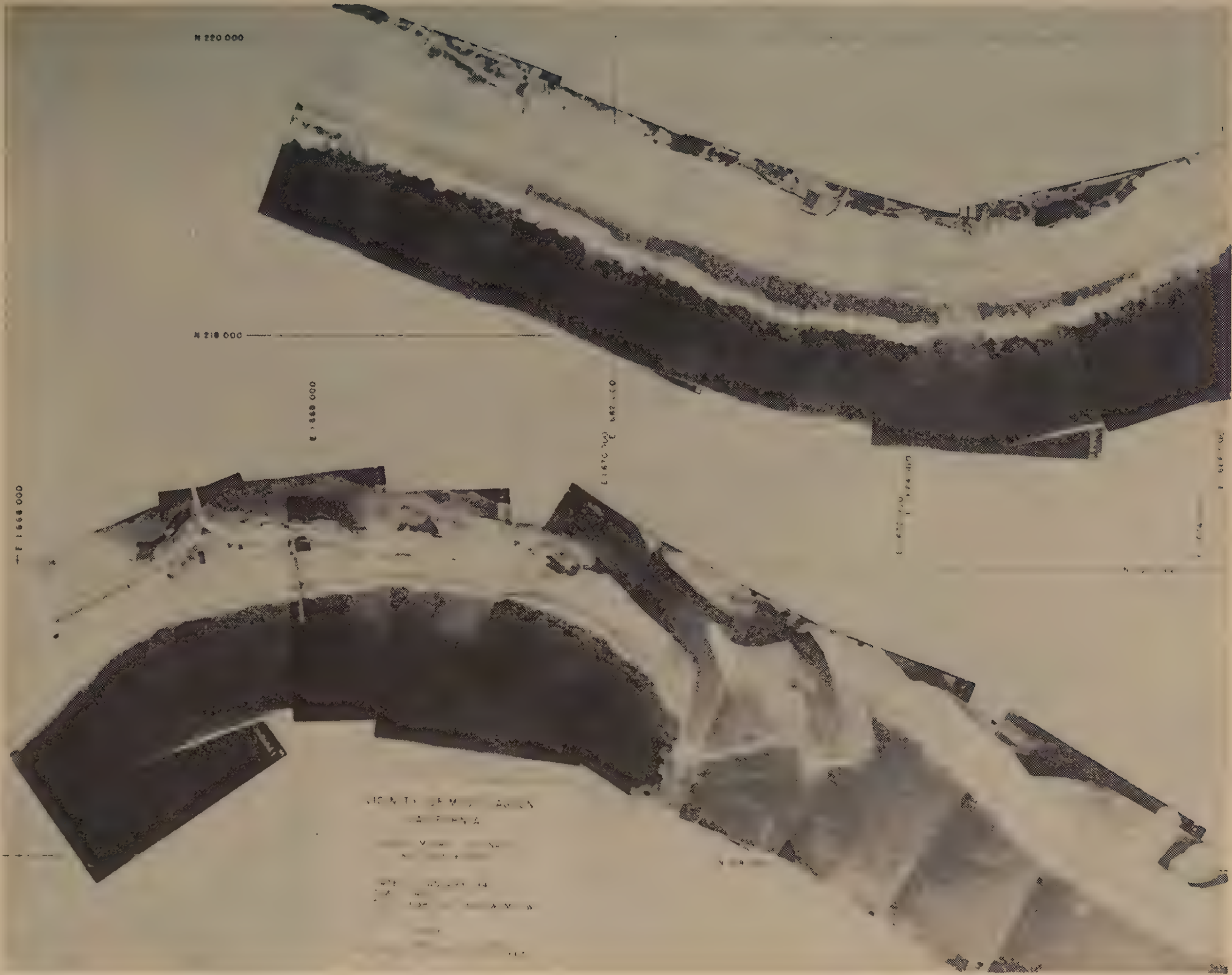
VICINITY OF MUGU LAGOON
CALIFORNIA
(AERIAL MOSAIC - U S NAVY)
ALTITUDE = 2000
DATE 5 DECEMBER 1948
TIME 400
TIDE EBB + 0 ABOVE MLLW
SCALE
0
500
1000
FEET
N 218 000
N 220 000
E 1 668 000
E 1 662 000
E 1 670 000
E 1 664 000
E 1 672 000
E 1 666 000

MUGU BEACH AND SAND SPITS PRIOR TO 17 DECEMBER 1948 STORM. NOTE THAT BEACH BERM IS APPROXIMATELY 50 FEET SEAWARD OF THE BUILDINGS BORDERING THE PIER. DREDGE IN THE LAGOON NORTH OF THE PIER IS DEPOSITING MATERIAL ON THE LAGOON SIDE OF THE SPIT, 1,500 FEET WEST OF THE PIER.

FIGURE 23

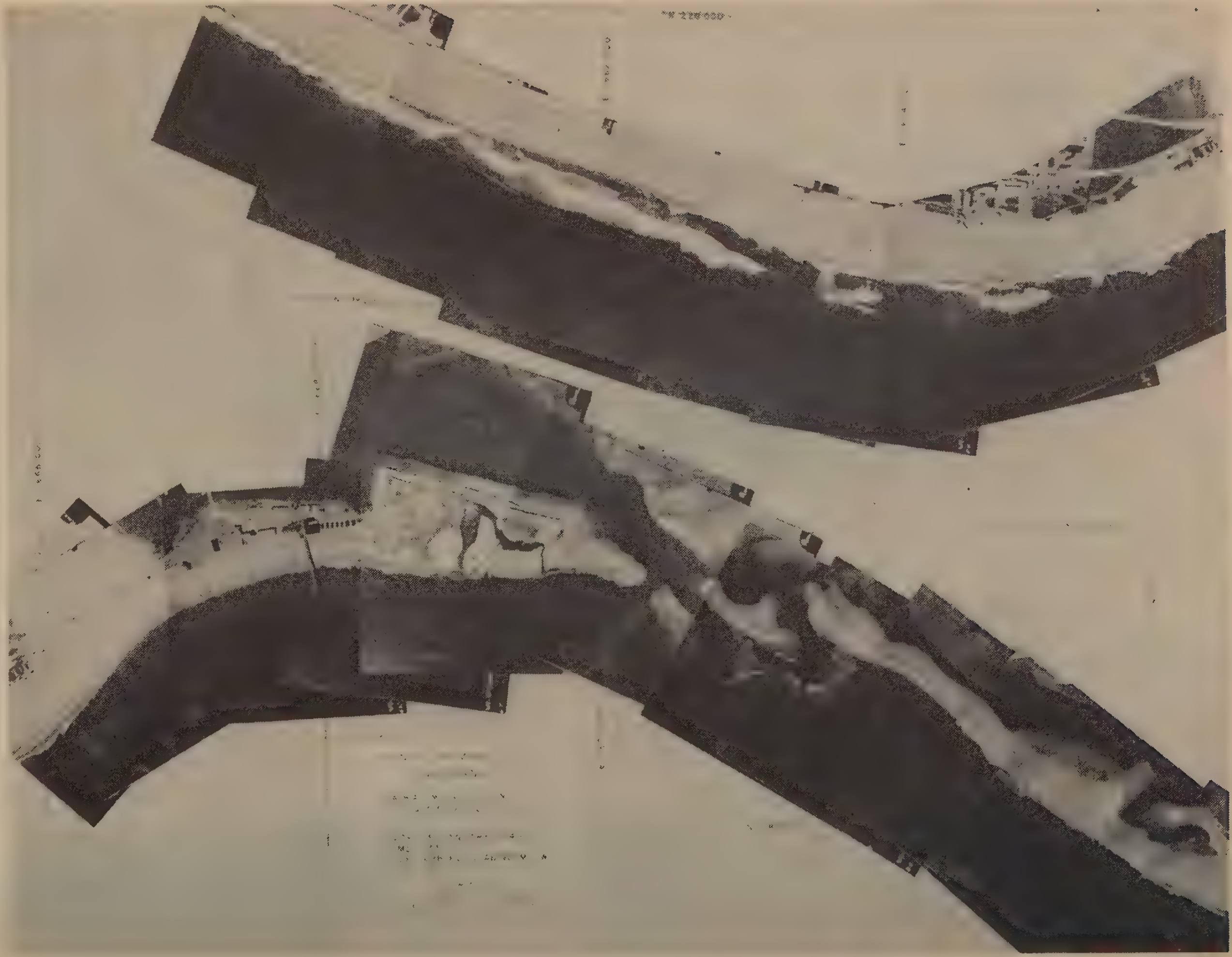


AERIAL PHOTOGRAPHS OF MUGU BEACH AND SAND SPITS SHOWING A NEW TIDAL INLET (2600 FEET EAST OF THE PIER) FORMED BY THE STORM OF 17 DECEMBER 1948 NOTE DREDGED MATERIAL DEPOSITED NEAR THE PIER AND BEACH BERM CUT BACK TO THE BUILDINGS BORDERING THE PIER. (COMPARE WITH FIGURE 23)

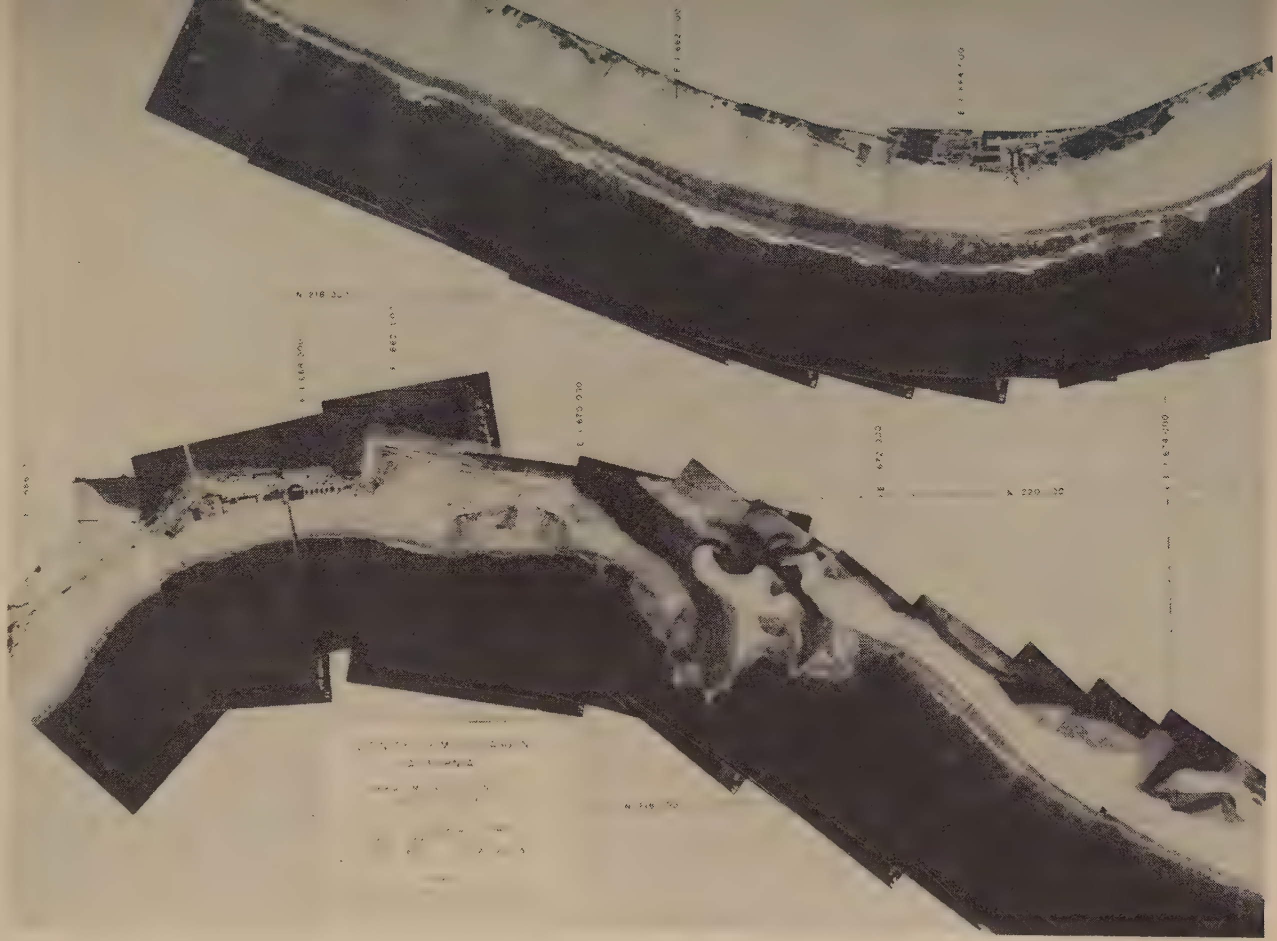

N 220 000
N 218 000

MUGU BEACH AND SAND SPITS ON 13 JANUARY 1949
NOTE THE TWO TIDAL INLETS.

FIGURE 25



MUGU BEACH AND SAND SPITS ON 31 JANUARY 1949 NOTE THE THREE TIDAL INLETS TO THE LAGOON, AND THE EXTENT OF THE ARTIFICIAL FILL. –



MUGU BEACH AND SAND SPITS ON 10 FEBRUARY 1949. THE BEACH FORESHORE HAS BEEN BUILT SEAWARD BY MATERIAL DREDGED FROM THE LAGOON FROM A POINT 1,300 FEET WEST OF THE PIER TO 2,000 FEET EAST OF THE PIER. BY 17 MARCH THE FILL HAD BEEN EXTENDED TO A POINT 3,200 FEET EAST OF THE PIER.

FIGURE 27

Contribution No. 454

LONGSHORE-BARS AND LONGSHORE-TROUGHS

TECHNICAL MEMORANDUM NO. 15
BEACH EROSION BOARD
CORPS OF ENGINEERS

JANUARY, 1950

Contribution from the Scripps Institution of Oceanography, New Series, No. 454

FOREWORD

This paper was prepared by Dr. Francis P. Shepard of the Scripps Institution of Oceanography and represents in part the results of research carried out for the U. S. Navy and the Beach Erosion Board. The report first appeared in limited issue as Submarine Geology Report No. 6 of the Scripps Institution of Oceanography, University of California. It is believed that the findings of the investigations are of sufficient value to merit publication at this time.

The opinions and conclusions expressed by the author are not necessarily those of the Board.

The authority for publication of this report was granted by an Act for the improvement and protection of beaches along the shores of the United States, Public Law No. 166, Seventy-ninth Congress, approved July 31, 1945.

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LONGSHORE-BARS AND LONGSHORE TROUGHS

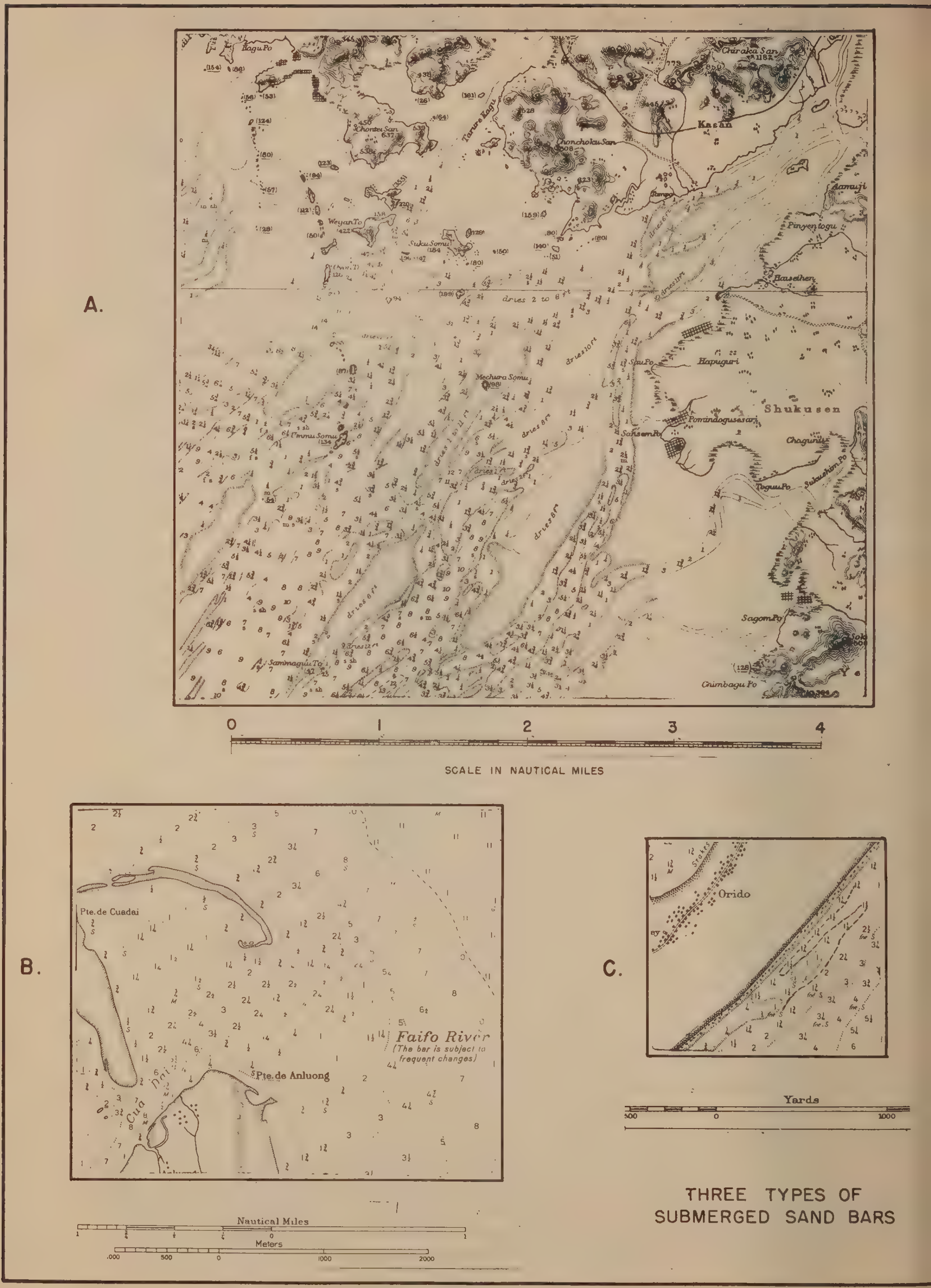
Abstract

The submerged longshore-bars and longshore-troughs which skirt the shores off most sandy beaches are described. The troughs which lie landward of the bars are explained as the result of plunging breakers and the longshore currents which are feeders to rip currents. The bars are thought to be partly the result of the excavation of the troughs and partly due to landward migration of sand outside the breakers and seaward migration from the troughs. The depths of the bars and troughs are shown to be related to wave and breaker heights. The elimination of some bars is seen to be the effect of a long continued period of small waves during which the bar moves landward filling the trough. In many areas the deeper bars persist undisturbed through long periods of quiet seas. The analysis of thousands of profiles, mostly taken along California open ocean piers, is the chief basis for the preceding conclusions.

Introduction

Because of their instability, submerged sand bars are a source of navigational difficulty to every type of craft from row boats to ocean liners. There appear to be three principal types of these shifting sand bars. One is crescentic in shape and is found off many river mouths and narrow entrances to bays (figure 1A). A second type is oval in shape and occurs in groups of somewhat parallel dune-like masses. Many of these are elongate parallel to the sides of straits and estuaries where there are strong currents and where abundant sediment is available (figure 1B). Others are more irregularly distributed. The third type of bar is long and narrow, extending essentially parallel to the shore line along most long sand beaches. The present discussion will deal only with this third type. This type presumably includes the cusp-like bars which were reported by King and Williams (9, p.75) from the shallow water along the margin of bays in the Mediterranean. King and Williams refer to the latter as crescent bars but they are decidedly different from the large crescents off bay entrances and are apparently more akin to beach cusps.

The term ball has been used to describe these shore-skirting bars, and their accompanying troughs, found inside the bars, have been referred to as lows. However, the word ball implies a roundish protuberance rather than an elongate ridge and low suggests a basin or valley, so that it seems advisable to use the more descriptive terms bar and trough for which there is ample precedent. In order to distinguish this type of bar from other types which include emergent bar beaches, a qualifying adjective is suggested so that they will be termed here longshore bars and longshore troughs.


A.
Kagu Po
Chontei San
Weyan To
Suku Somu
Tarure Kogu
Choncholcu San
Chiraka San
Kasan
Aamuji
Pinyentogu
Baseihen
dries 2 to 8 ft
Mechura Somu
Ummu Somu
Sau Po
Hapuguri
Shukusen
Sansem Po
Toguu Po
Sukushim Po
Sagom Po
Sammaguu To
Chimbagu Po
0
1
2
3
4
SCALE IN NAUTICAL MILES
B.
Pte. de Cuadai
Cua Dai
Pte. de Anluong
Faifo River
(The bar is subject to frequent changes)
Nautical Miles
Meters
500
0
1000
2000
C.
Stakes
Orido
Yards
500
0
1000

THREE TYPES OF SUBMERGED SAND BARS

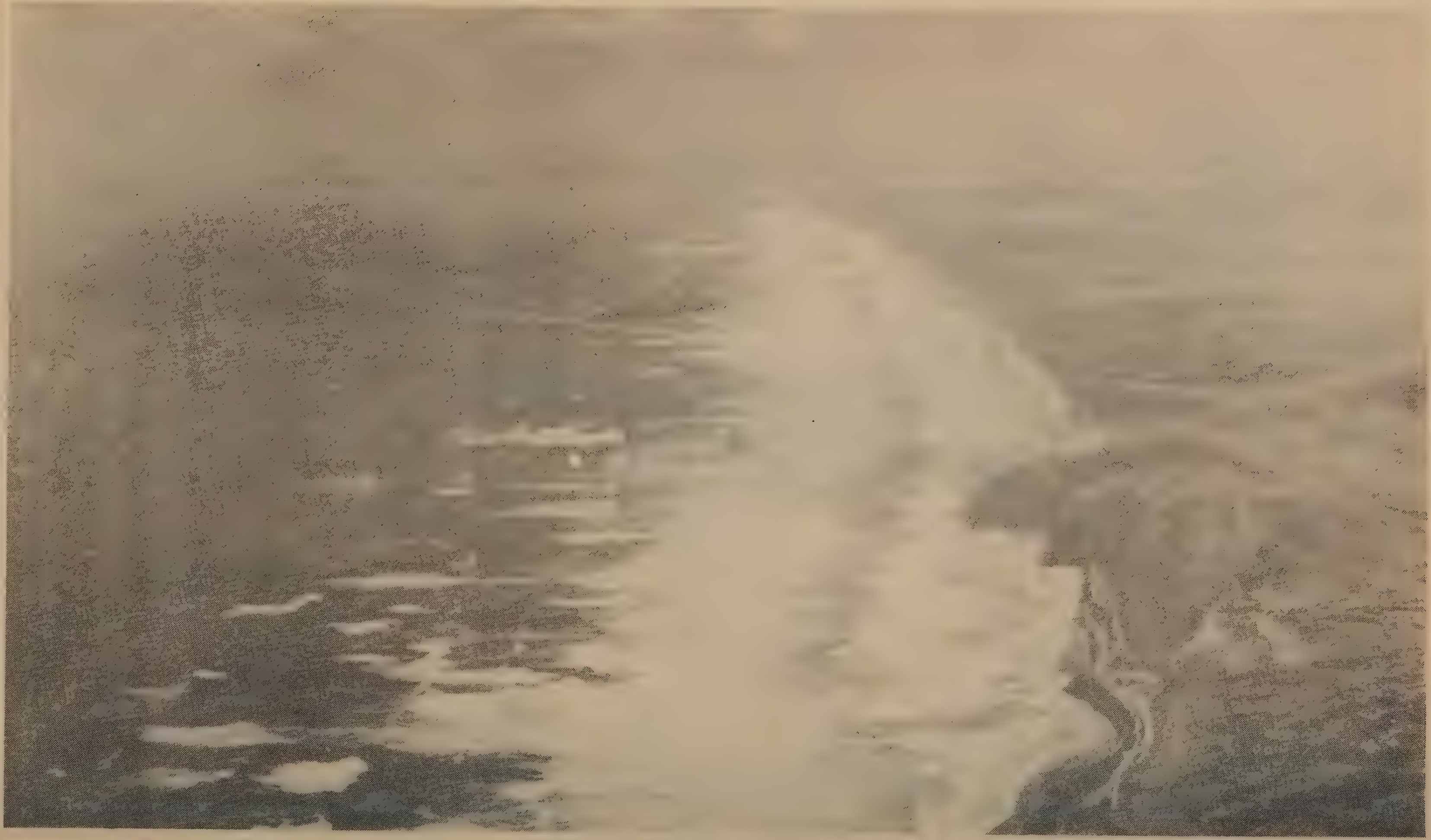
FIGURE I

Anyone accustomed to surf swimming along relatively straight sandy beaches can hardly have failed to encounter the longshore-bars and troughs while wading out into the breakers. During periods of high waves the longshore-bars can be detected from any high place which commands a view of the surf zone, because the waves break along these shoal ridges (figure 2) and usually re-form on the inside breaking again either on inner longshore-bars or on the low tide terrace, a feature which is very common near the low tide level. If the water is clear during periods of small waves, the bars can be seen as variations in the color shading in the water along the shore.

Longshore-bars have been described by various authors, and suggestions have been made regarding their origin. A good summary of the earlier literature will be found in Johnson (6) and in Evans (2). A considerable number of profiles of the longshore-bars were made by German investigators, notably Otto (10) who studied a series of bars over a period of five years. Measurements by the U. S. Coast and Geodetic Survey (15) provided other information. Profiles of the longshore-bars of Lake Michigan were made by Evans who attempted also to determine the variation in position of these bars during one summer.

The work of Keulegan (6) with the Beach Erosion Board during and following World War II produced valuable wave-tank observations and an analysis of the mechanics involved in bar formation. Extensive field studies of longshore-bars were initiated during the war by the Department of Engineering of the University of California (Berkeley). Most of this material is not yet published although numerous profiles from various parts of the west coast have appeared as mimeographed laboratory memoranda from the Berkeley group. Important investigations were also conducted by King and Williams (9) which included field and tank observations.

At Scripps Institution information on longshore-bars has come particularly from daily measurements made along the 1,000-foot Institution pier during 1937 and 1938 (14) Subsequent measurements along this pier were made at various intervals, and profiles have been obtained along seven other California piers, all of which revealed the existence and the changing positions of bars. The pier profiles, particularly those made daily in 1937 and 1938, provide the greatest source of information for the present report since they contain the only available information on the changing depths and positions of the bars and troughs which can be definitely related to short period changes in waves, currents, tides, and winds. In a sense it is unfortunate that this information should come from pier profiles since piers form a sufficient obstruction both to waves and currents to set up special conditions. On the other hand nothing has as yet been developed to take the place of pier soundings for making accurate profiles through large breakers. Self-propelled sea sleds (4) may form an exception of this statment, but they have not been very successful. The breaker zone is the locus for bar and



AIR VIEW OF WAVES BREAKING ON LONGSHORE – BAR
ALONG WEST COAST NORTH ISLAND, NEW ZEALAND
(PHOTOGRAPH BY WHITES AVIATION, LTD., NEW ZEALAND)
FIGURE 2

trough development. Measurements with Dukws, the amphibious vehicles developed during the war, are fairly satisfactory during small-surf periods, but these periods are not as significant as large-wave periods. No records are available in which profiles were repeated at short intervals during which a daily check on sea conditions had been made.

Adequacy of Pier Profiles as a Source of Information

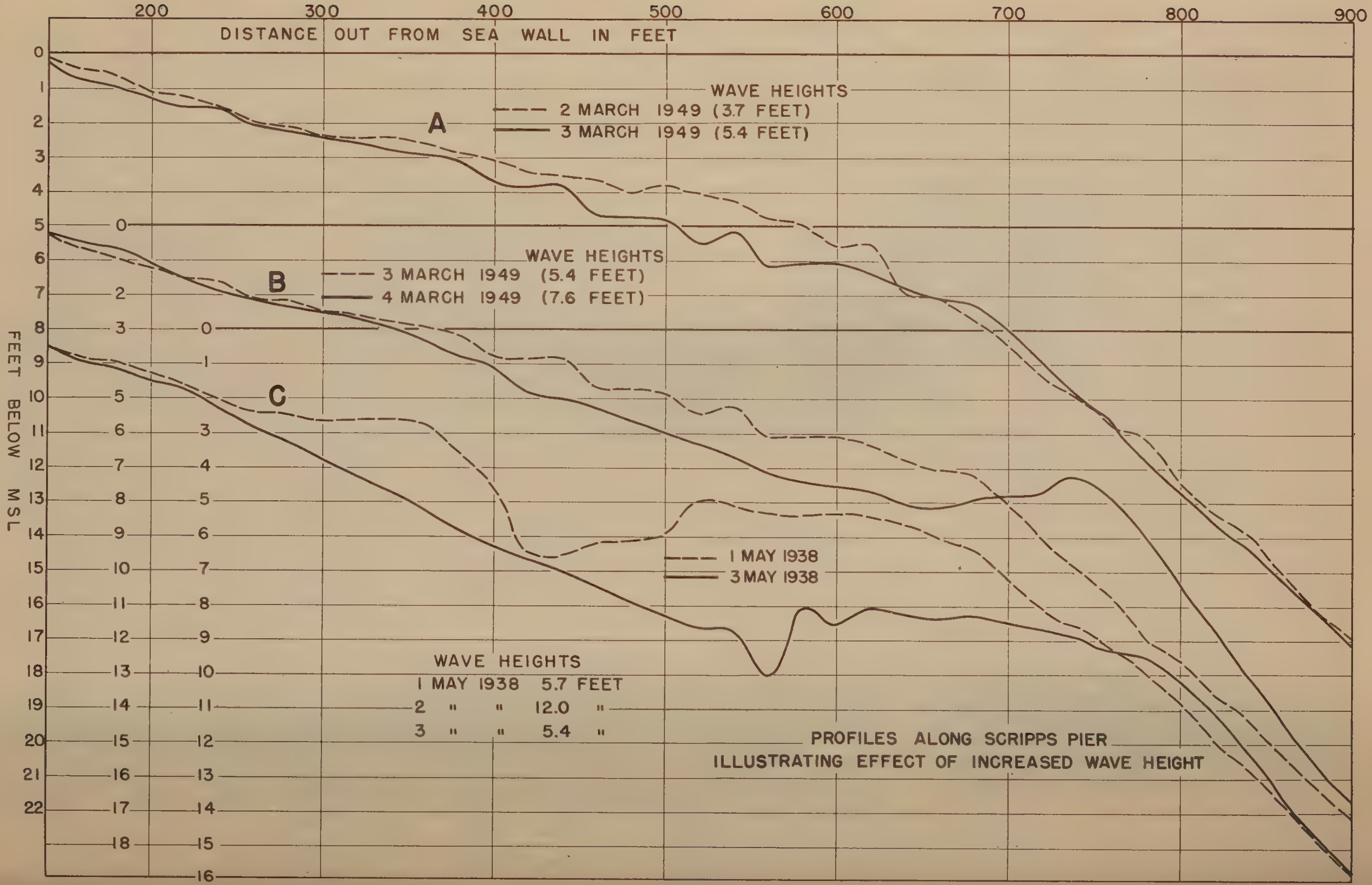
Since much of the information for the present discussion comes from pier profiles, some justification seems required of the use of this evidence from locations which are under special influences. Evans (2, p. 479) observed that the bars along the east shore of Lake Michigan were disturbed and broken up in the vicinity of piers. The piers tend to deflect longshore currents seaward as rip currents which in turn develop gaps in the bars. However, rip currents are not particularly common along Scripps pier. A much more common rip exists somewhat north of this pier. Furthermore the longshore-bars appear to be well developed along the piers of southern California and, so far as can be told from somewhat fragmentary information, do not appear to be particularly different from the bars on either side. As will be shown subsequently, the changes of bars and troughs have a definite relationship to wave and current conditions. Therefore it seems likely that the changes in the pier profiles are a fairly reliable index of what is happening on either side. Finally, the soundings were taken half way between piles where the least effect would occur and, in the case of the Scripps pier, a boom extended the sounding wire 10 feet outside the rail, further decreasing the piling influence.

If at some time in the future information becomes available from the slopes which are entirely free from pier influence, it will no doubt be more satisfactory. However, an enormous amount of difficult work must be accomplished before sufficient information is available to replace that coming from the thousands of pier profiles.

Characteristics of Longshore-bars and Longshore-troughs

King and Williams (9) express the opinion that the feature referred to here as a longshore-bar is typical only of "tideless seas" such as the Mediterranean and Baltic, and that another type which they call ridge and runnel is found exposed by low tide on beaches having large tidal ranges. The present investigations in areas where appreciable tidal ranges operate make this distinction seem of no great importance, although it may well be that the longshore-bars in the areas of large tidal range are less continuous and cut by more channels, partly as a result of runoff from the exposed troughs during low tide.

The study of the hundreds of west coast profiles shows a relationship between the depths of longshore-bars and longshore-troughs. If as suggested by Passarge (11) the longshore-bars are built by sediment thrown shoreward by the breaking waves, there should be excavation of a trough on the outside and building of a ridge on the inside of the



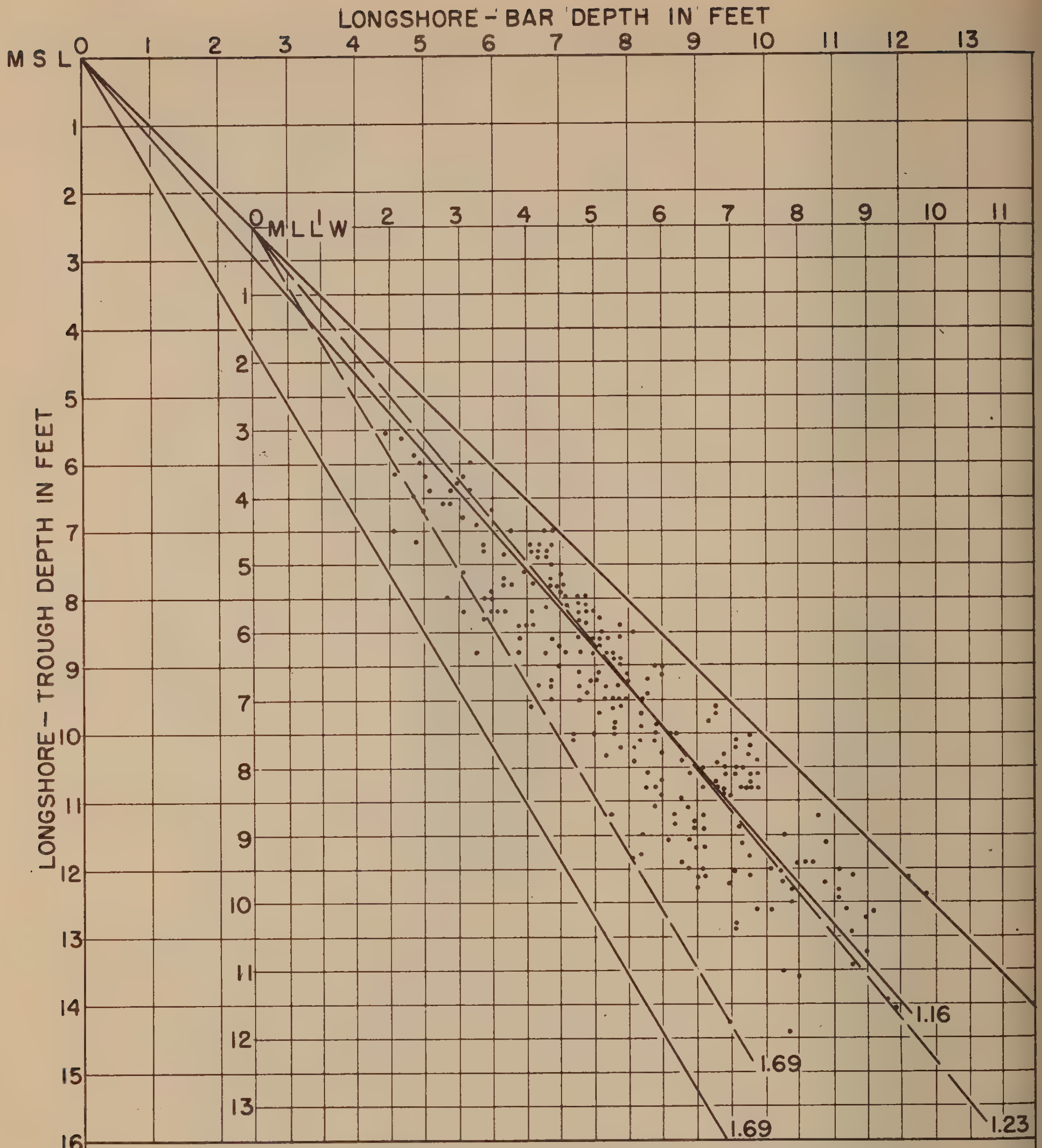
PROFILES ALONG SCRIPPS PIER
ILLUSTRATING EFFECT OF INCREASED WAVE HEIGHT

FIGURE 3

plunge point. A longshore-bar formed in this way should have a trough cut into the sand slope outside the bar, whereas the slope inside should remain essentially unchanged. Furthermore, the bars should form shoreward of the breaking waves. The daily profiles along the Scripps pier show that virtually all of the large longshore-bars form slightly seaward of the plunge points of the larger breakers occurring at the time the profile was measured. Furthermore, the trough is excavated on the inside and the bar is either left as an erosion remnant or is built up outside the trough (figures 3 and 18). This relationship is substantiated by the numerous cases where bars are found which have no concavity in the offshore slope outside and was suggested previously by Evans but without supporting evidence. It is also indicated in Keulegan's tank experiments.

Most profiles show more than one bar. In some places, as described by Evans (2) there are several parallel bars comparable in size and extending for many miles along the shore. Plane photos demonstrate such features along the shores of Texas, Louisiana, Lake Michigan, and Chesapeake Bay (8). The lines of breakers in plane photos showing the bars along other coasts indicate less continuous features and in many places suggest that only one significant bar exists. The pier profiles of southern California suggest that at least in this area one bar is much larger than any others which may exist. A count of the 1937-38 profiles at Scripps pier shows 209 with indications of one or more bars in addition to the large bar, whereas 90 profiles show only one bar. The remaining 54 profiles gave no indication of the existence of a bar. Evans found that in general the distance between the second and third longshore-bar is greater than that between the first and second, and that the bars grow successively deeper away from shore. This appears also to be true of most of the Oregon and Washington profiles reported by Isaacs (5). On the other hand no rule could be found relative to the plural longshore-bars measured along the Scripps pier. In a considerable number of cases the outer bar, which was the largest, stood higher than that directly inside.

Longshore-bars are very common off gently sloping sand beaches. So far as can be ascertained, steeply sloping beaches, that is, beaches where foreshore slopes are in excess of about 4°, have only very narrow insignificant bars. During the investigation of beach profiles in Oregon and Washington, Isaacs discovered that bars were not present in bays of small dimension. The report by King and Williams (9) of cusp-like bars in such localities is significant. The profiles suggest that longshore-bars and longshore-troughs do not exist outside of the zone where waves break during periods of high surf. However, so many of the sections establishing the existence of the bars terminate at depths near this outer limit that the statement may not be valid. Other types of submerged bars are known to exist at greater depth (16, chart V).



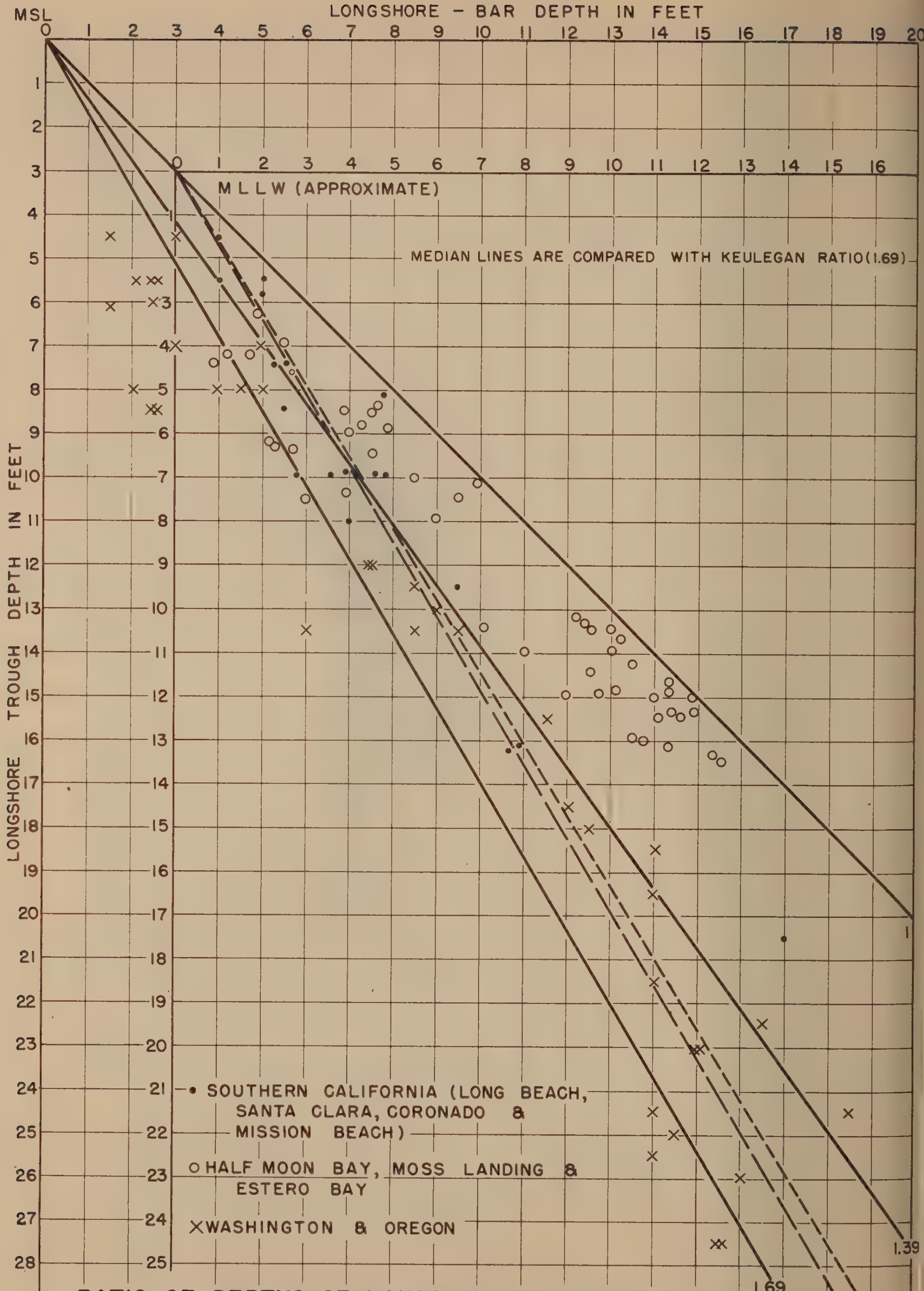
RATIO OF DEPTHS OF LONGSHORE—TROUGHS AND LONGSHORE—BARS AT SCRIPPS PIER

MEDIAN LINES ARE COMPARED WITH KEULEGAN RATIO (1.69)

FIGURE 4

Ratios of bar and trough depth are influenced by a number of
ariables of which the most important is the slight deepening which is
ound along the axis of the trough towards gaps in the bars. As a
esult largely of his tank experiments, Keulegan came to the conclusion
hat the depth of longshore-bars and longshore-troughs below still-water
evel showed a fairly constant relation such that the depth of the
rough divided by the depth of the bar is approximately 1.69. A small
umber of profiles from Lake Michigan and the Baltic Sea seemed to
erify his ratio. A test of the ratio was made from a much larger
umber of beach profiles using both mean sea level and mean lower low
ide level instead of still-water level. The best reference level
or this comparison is not easily determined. The rate of tidal
luctuation is small near the low and high tide marks, but it is
lso small between a low high and high low which are closely similar
n height. The average height of the tide in the latter stage is
lose to mean tide (figure 14). One advantage of using mean lower
ow tide is that under some circumstances, particularly with large
aves, the longshore-bars and longshore-troughs developed at the
igher levels may be eliminated at low tide level whereas the low tide
ars and troughs are likely to persist during high tides. A plot of
hese relations for 276 cases at Scripps pier (figure 4) shows that
he mean relationship is 1.16 using mean sea level, or 1.23 using
ower low tide. A much smaller number of sections along other
alifornia piers shows a relationship of 1.40 for mean sea level, or
.63 for lower low tide, for the troughs to bars. A series of 116
rofiles taken out from west coast beaches by the Engineering Depart-
ent at the University of California, Berkeley, and by the Corps of
ngineers, U. S. Army, gave a value of 1.39 using mean sea level,
r 1.63 using lower low tide (figure 5). However, considering only
he profiles reported by Isaacs (5) off Oregon and Washington, the
atio is close to that of Keulegan, being 1.60 using mean sea level,
r 1.93 using lower low tide. This area is one of very large waves,
0-to 30-foot breakers being common during storms. A series of east
oast profiles largely off Cape Cod (figure 6) indicate 1.34 using
ean sea level, or 1.47 using mean low tide, for the average trough
o bar ratio. All of these diagrams show a considerable spread
n the ratio and in general indicate that the ratio decreases with
epth. The ratios for mean sea level for the 4 groups average 1.3,
r 1.5 for mean low water. The discrepancy with Keulegan's ratios may
e explained because his sources of information were tank experiments
hich had bars and troughs of small amplitude.

Keulegan considered also that there was a common ratio between
epths of the bar and what he called the bar base. He defined the
atter as the line connecting the trough and the barless profile
utside the bar. His experiments indicated that the depth of the
ar had a ratio to the depth of the bar base, directly underneath
he bar, of 0.58. This ratio was also tested from the beach profile.
he large number of Scripps pier profiles shows the ratio for mean
ea level to be 0.77. or 0.70 using lower low tide (figure 7). How-
ver, the profiles at other piers give 0.58 using mean sea level,
r 0.46 using lower low tide. The west coast beach profiles give a



RATIO OF DEPTHS OF LONGSHORE - TROUGHS AND LONGSHORE - BARS - MSL & MLLW

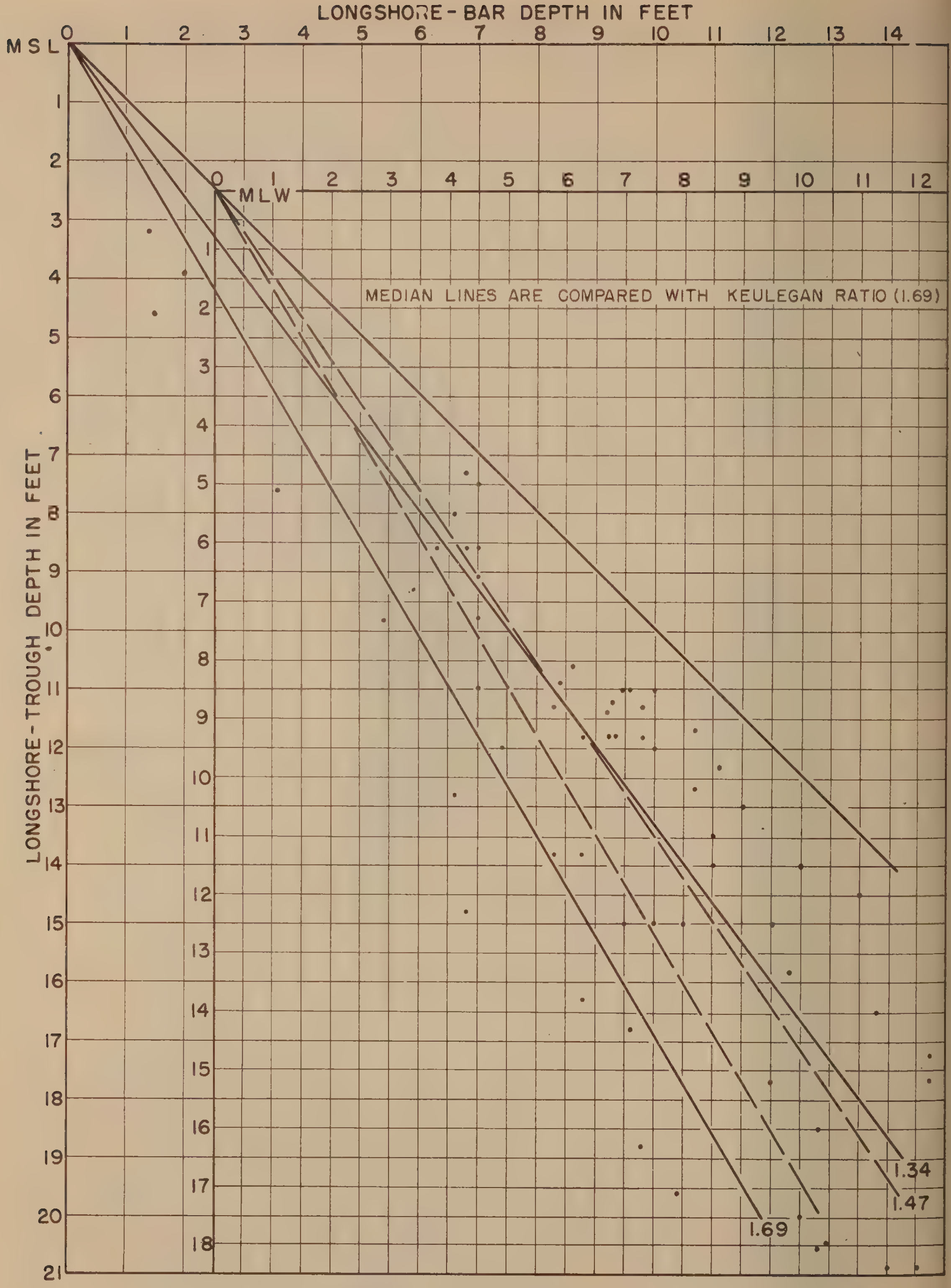
FIGURE 5

ratio of 0.63 using mean sea level, or 0.53 using lower low tide (figure 8), with distinctly higher ratios for the greater depths. The profiles off Oregon and Washington have a ratio of 0.57 using mean sea level, or 0.46 using lower low tide. The east coast sections largely off Cape Cod gave a ratio of 0.59 using mean sea level, or 0.53 using mean low tide (figure 9), also close to that of Keulegan. The average ratio for the 4 groups for mean sea level is 0.63 or 0.55 using lower low tide. Thus the Keulegan ratio for these parameters checks very well.

Relation of Bars and Troughs to Wave Height

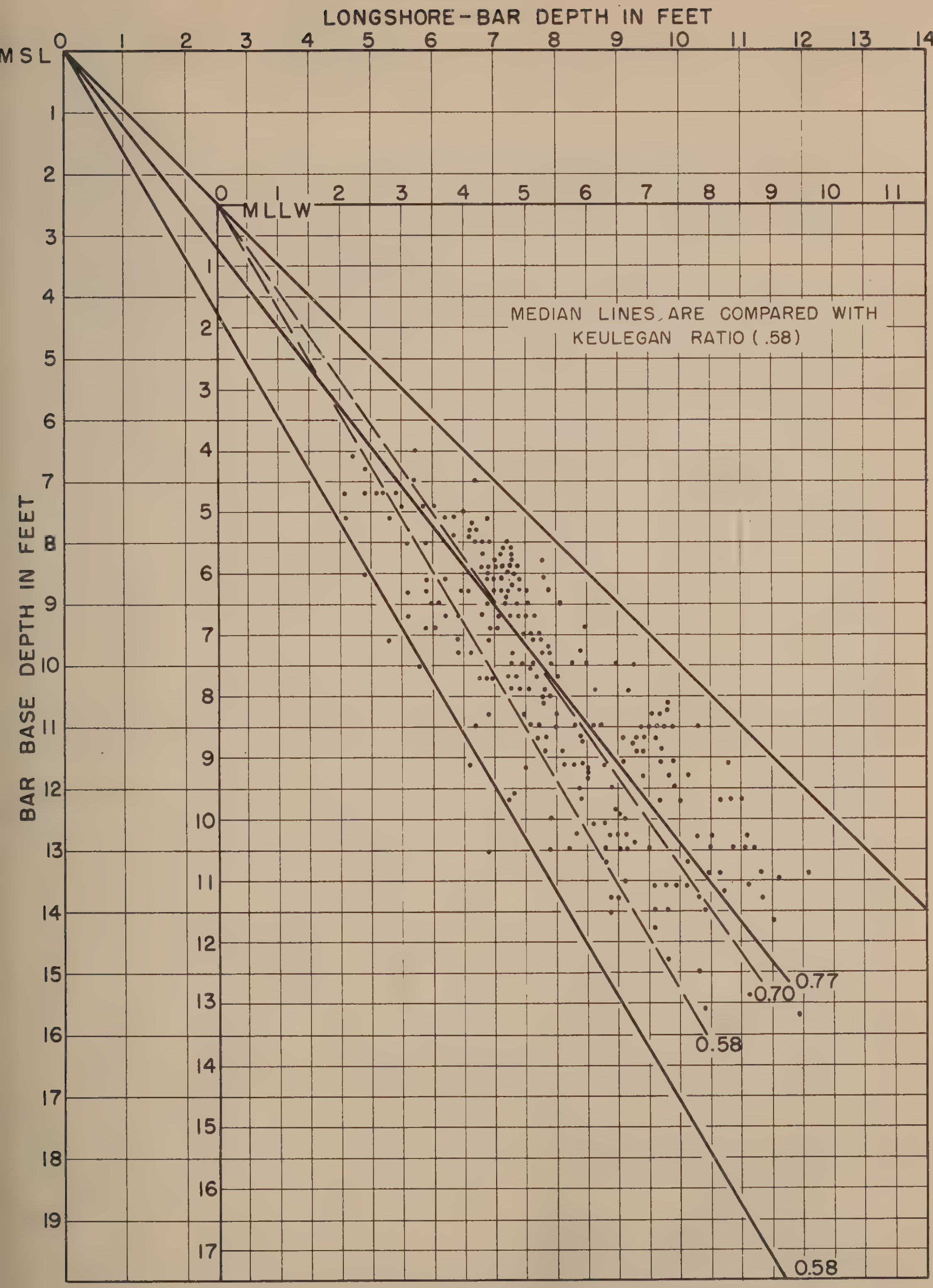
Evans, Keulegan, and King and Williams all recognized the relationship between the wave size and bar depth. This relationship becomes still more evident from the study of the profiles taken along the California piers. The most substantial data were derived from the profiles along Scripps pier (figure 10). A plotting of bar depth against the wave heights which were measured daily shows a grouping of points around the median line but having a rather large spread. The same relation comes from the plot of trough depths against wave height (figure 11). The quartile lines in figures 10 and 11 drawn parallel to the median line indicate that more than 50% of the points lie within one foot of the median line. There can be little doubt but what deeper longshore-bars and longshore-troughs are found on the days of larger waves. The relationship was also tested by plotting the greatest wave height of the preceding 5 days against the bar depth (figure 12), but this does not group the points as close to the median line as did the plotting with accompanying wave heights.

A comparison of some of the daily profiles to changing wave heights indicates the nature of changes which take place (figures 3, 13, and 18). The complete record for the 1937-38 measurements of depth changes of both the longshore-bar and longshore-trough along with wave height and bar height above the trough is given in figure 14. The fact that the response to changing wave conditions is similar throughout the years leaves little doubt of the reality of this relationship. The bars accompanying relatively small waves are cut away by the large waves and new bars from outside. However, the building up of the new bars may lag so that the first effect of a day of large waves is likely to be a cutting away of the old bar and the excavation of a deep trough inside rather than the building of a new bar on the outside. The new bar often develops after the large waves have subsided. A comparison of the wave record over the year with the cross-sectional area of the bar is also instructive (figure 15). This cross-sectional area is derived by drawing a horizontal line out from the bottom of the trough to the point where the line intersects the outer slope and computing the area of the bar above the line. The bars clearly increase in size during the season of large waves, but the increase generally lags after a particular period of large breakers. Longshore-bar and longshore-trough depths show a relationship to maximum wave heights. Thus the bar crests off southern California are



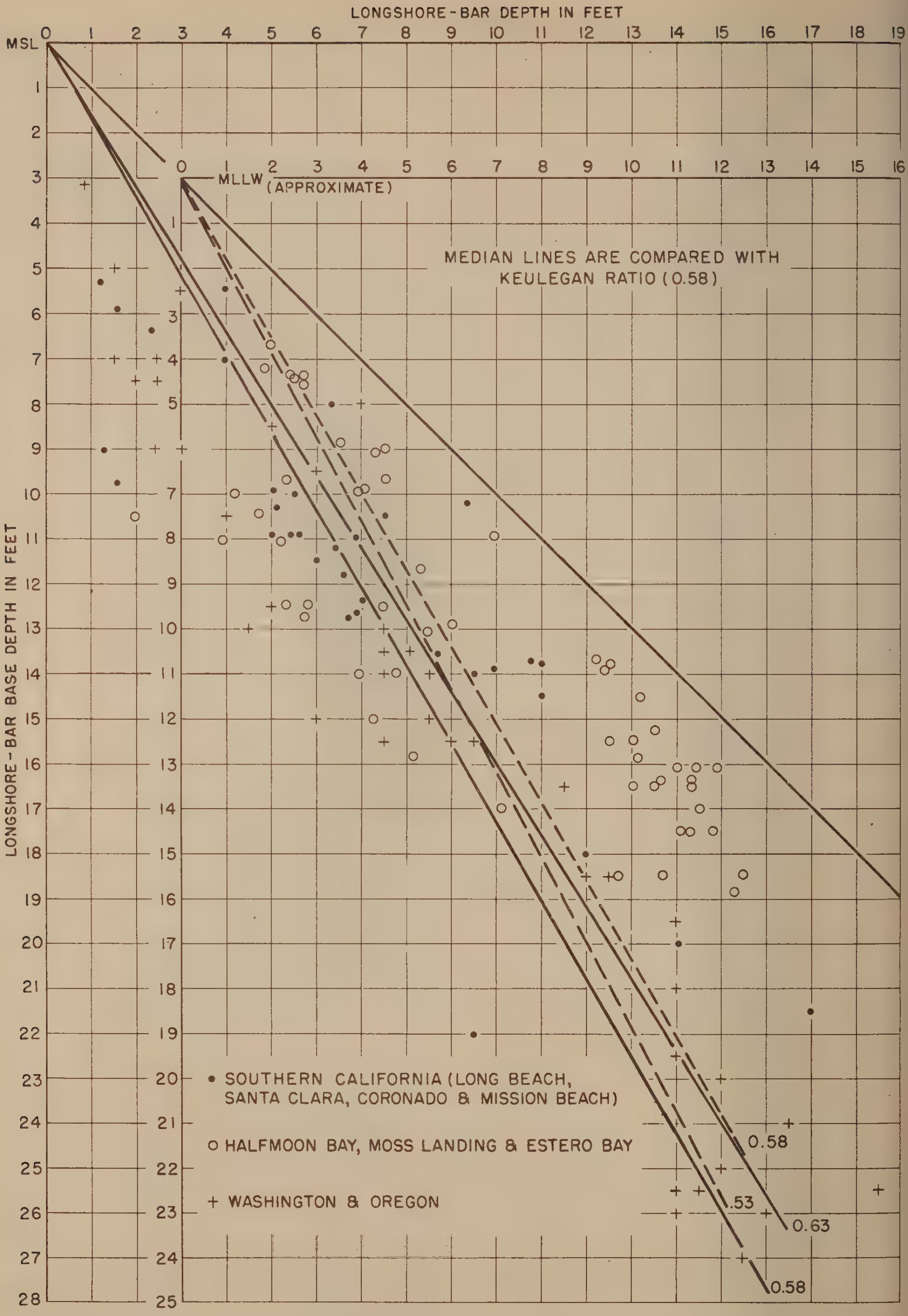
RATIO OF LONGSHORE-TROUGHS TO LONGSHORE-BARS
U.S. EAST COAST

FIGURE 6



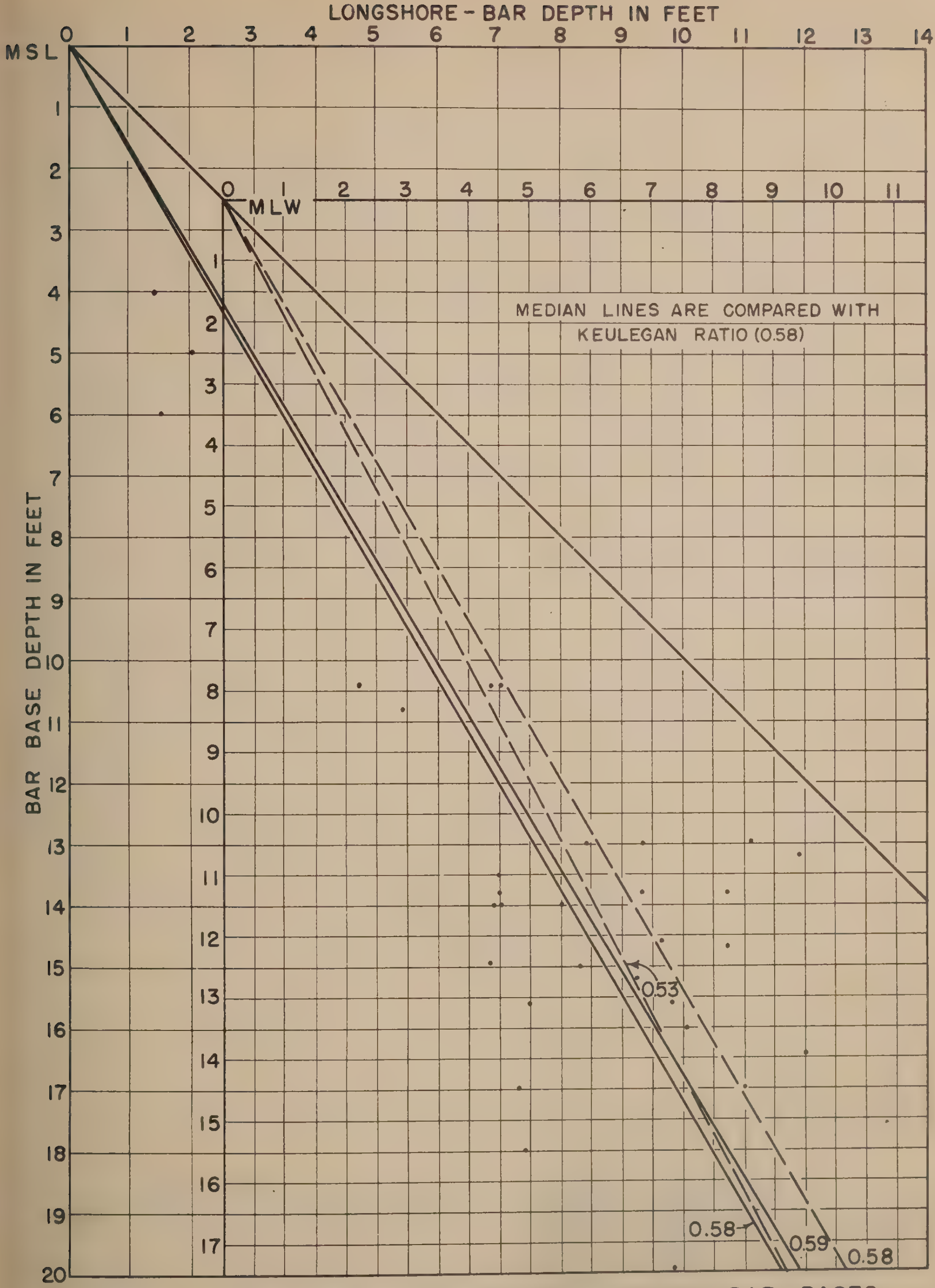
RATIO OF DEPTHS OF LONGSHORE-BARS TO BAR BASES AT SCRIPPS PIER

FIGURE 7



RATIO OF DEPTHS OF LONGSHORE BARS TO BAR BASES—MSL & MLLW

FIGURE 8



RATIO OF DEPTHS OF LONGSHORE - BARS TO BAR BASES
U.S. EAST COAST

FIGURE 9

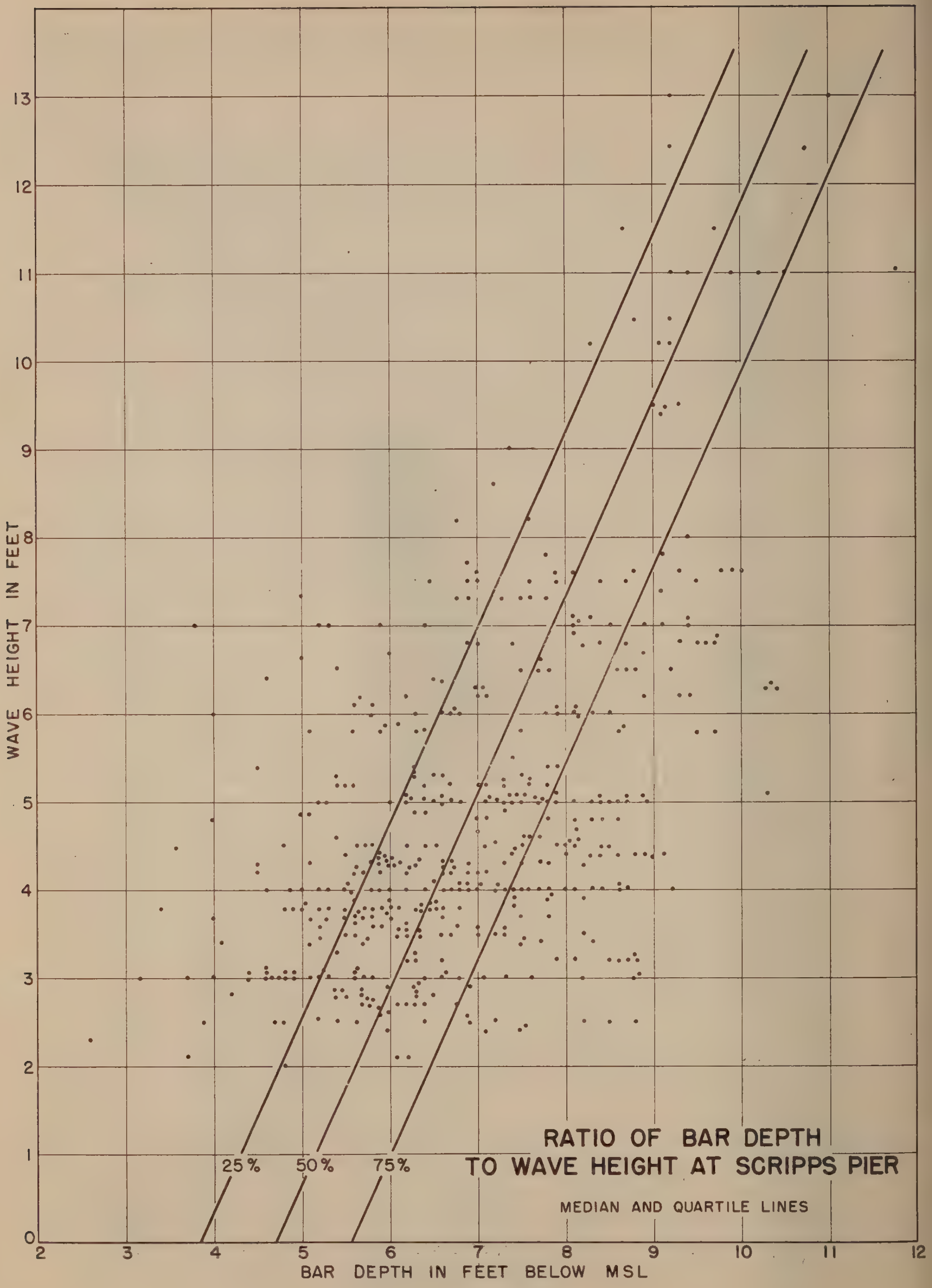
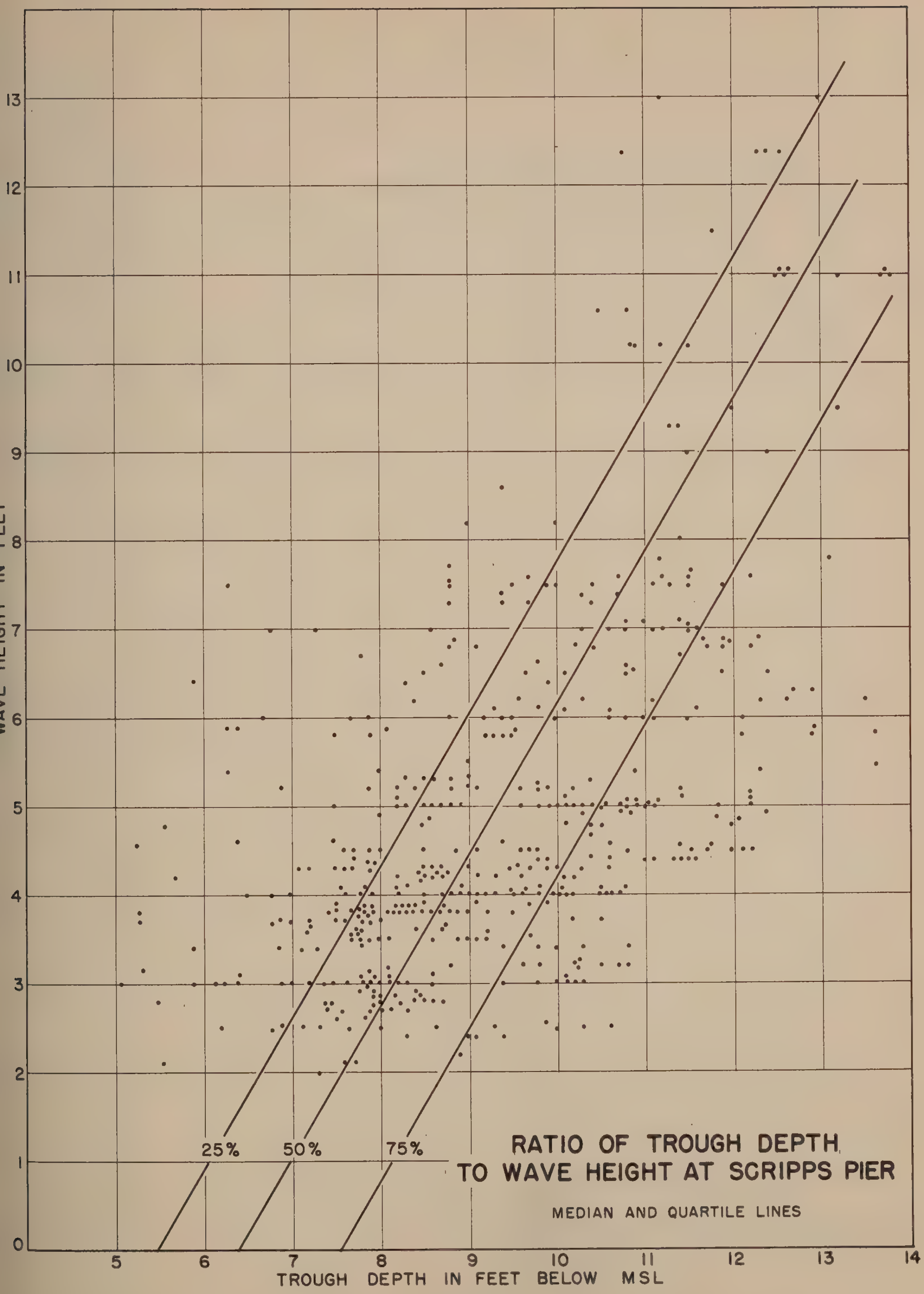

RATIO OF BAR DEPTH
TO WAVE HEIGHT AT SCRIPPS PIER
MEDIAN AND QUARTILE LINES
25%
50%
75%
WAVE HEIGHT IN FEET
BAR DEPTH IN FEET BELOW MSL
0
1
2
3
4
5
6
7
8
9
10
11
12
13
2
3
4
5
6
7
8
9
10
11
12

FIGURE 10



RATIO OF TROUGH DEPTH TO WAVE HEIGHT AT SCRIPPS PIER

MEDIAN AND QUARTILE LINES

FIGURE 11

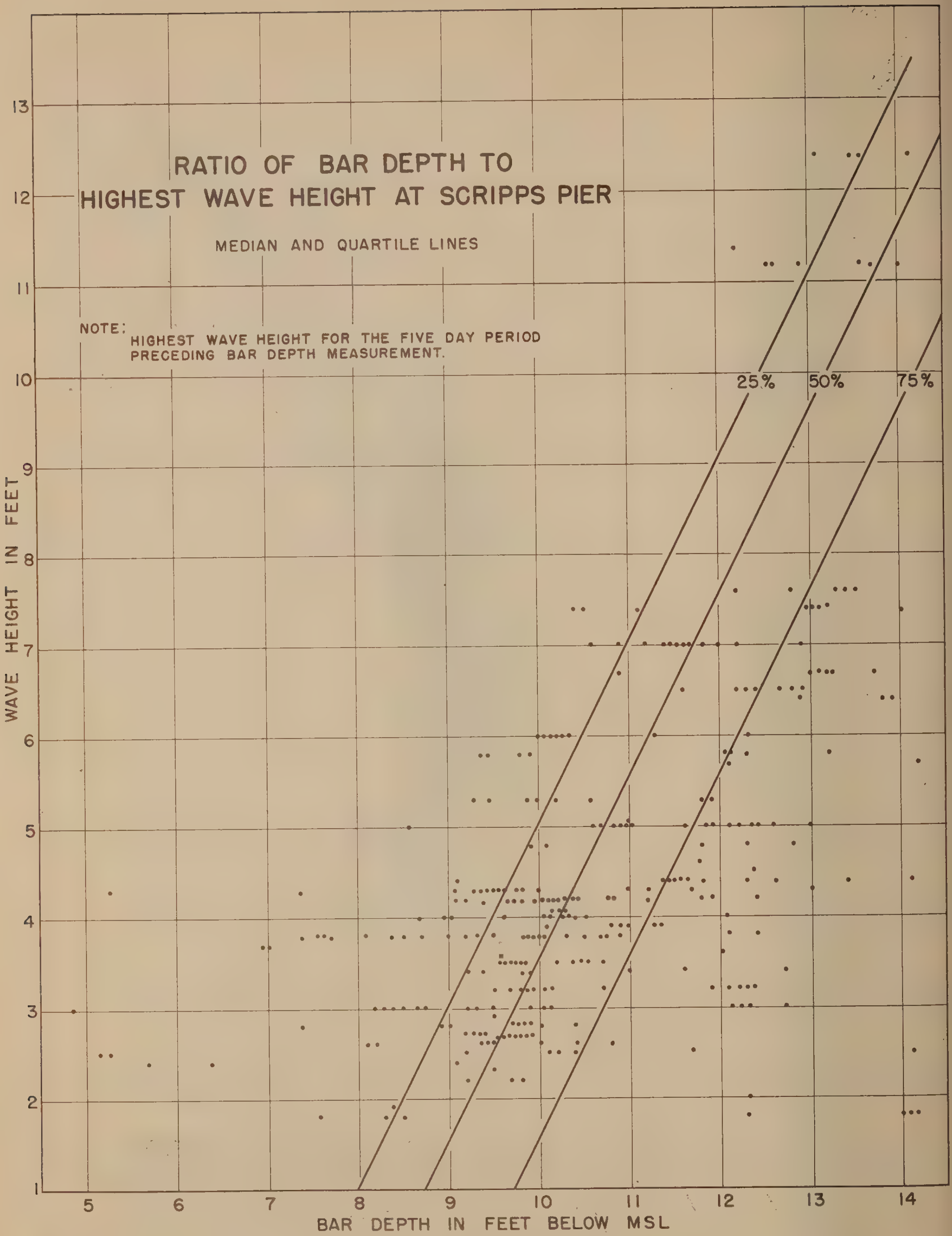
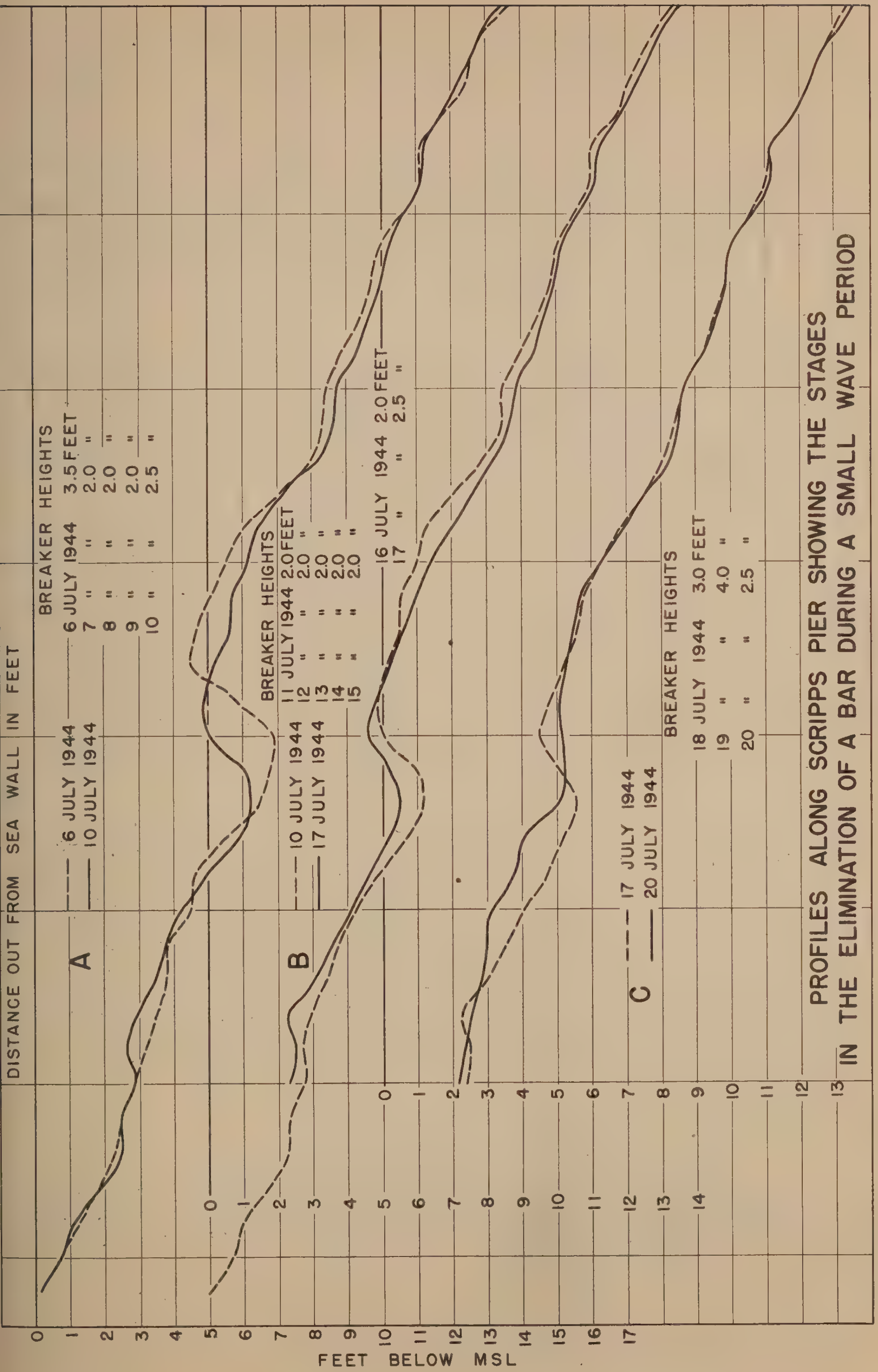

RATIO OF BAR DEPTH TO
HIGHEST WAVE HEIGHT AT SCRIPPS PIER
MEDIAN AND QUARTILE LINES
NOTE: HIGHEST WAVE HEIGHT FOR THE FIVE DAY PERIOD PRECEDING BAR DEPTH MEASUREMENT.
25%
50%
75%
WAVE HEIGHT IN FEET
1
2
3
4
5
6
7
8
9
10
11
12
13
5
6
7
8
9
10
11
12
13
14
BAR DEPTH IN FEET BELOW MSL

FIGURE 12



PROFILES ALONG SCRIPPS PIER SHOWING THE STAGES IN THE ELIMINATION OF A BAR DURING A SMALL WAVE PERIOD

FIGURE 13

almost all less than 10 feet below mean sea level. In this area breakers are rarely greater than 10 feet. Off Washington and Oregon 20-foot waves are fairly common and bars extend to depths of at least 18 feet. This difference can be seen by the groupings of points from southern California and from Washington and Oregon in figure 5.

A plotting of the bar depth at a series of piers in southern California was made in relation to the seasonal change (figure 16). All of the bars and troughs shoaled as the summer period of small waves advanced. A similar effect over a much longer period is shown by the depth of the bars and troughs along the Scripps pier during a 8-year period (figure 17).

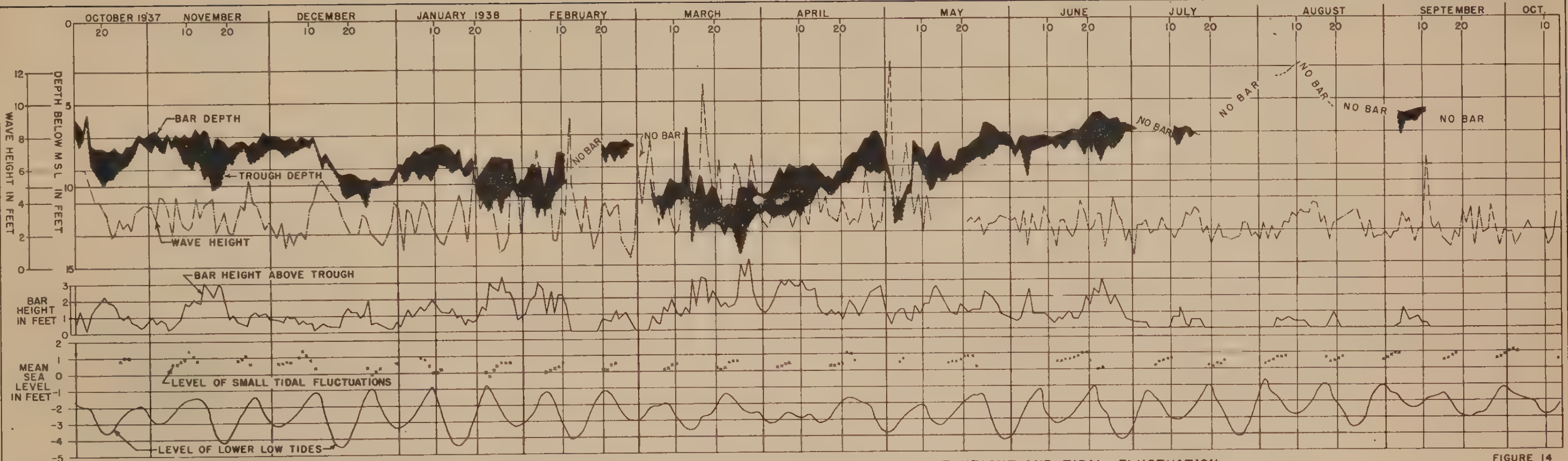
Relation to Currents

The data do not permit as good a correlation between longshore-bar and longshore-trough development and currents as is possible with wave height. Currents were observed but not measured at several points along the Scripps pier during most of the period of daily sand measurement, and a Sverdrup-Dahl current meter was in use at the end of the pier during most of the time. It is unfortunate that there is not a complete record of currents in the zone of bar and trough development. However, out of 98 observations in this zone only 9 showed currents in a different direction from the currents observed at the pier end at the same time. There appear to be some striking relations between the area of the longshore-bar and the current direction (figure 15). South currents apparently increase the area of the bar and the strongest recorded south current was observed just before the bar grew to its largest area. North currents conversely appear to have the effect of decreasing the bar area. One case where large waves were accompanied by excessive fill took place in February, 1938, during a period of north currents (figure 18, A).

A profile obtained at Oceanside pier at a time of very large longshore currents inside the breakers indicated a very large bar and trough. Other evidence suggesting that strong currents are an important factor, at least in the formation of troughs, comes from the finding of deep troughs along the path of the longshore feeder currents to rip currents during times when the currents are particularly strong (13, pp. 350-352). When these channels are exposed by low tide, current ripples are found in them indicating flow along their axes (5). Isaacs reports that these ripples increase in magnitude along the troughs towards the rip channels which cross the bars. Near these cross channels he found giant ripples similar to those in tidal channels.

Relation to Tides

The longshore-bars and longshore-troughs are necessarily dependent on the tides since waves break farther out on the offshore slope during low tides than during high tides. The large range during spring tides



CHANGES IN THE LONGSHORE-BAR AND TROUGH DEPTHS AT SCRIPPS PIER IN RELATION TO WAVE HEIGHT AND TIDAL FLUCTUATION

FIGURE 14

cause a shifting of position of deposition and cutting. This was clearly shown during a 36-hour period of continuous profile measurement. The result of this shift should be a greater development of bars and troughs during or shortly after neap tides when the breaker line remains more constant in position. A similar effect comes from the small ranges between the contiguous low high and high low which accompany neap tides.

Examination of the bar development during 1937-38 shows that other influences such as wave height and current variation are more important than tide, but there is a rough correlation between the larger bars and neap tide periods (figure 14). The first of the records showed somewhat of an inverse ratio to tide stage because of the development of large waves at spring tide, but the more typical relationship is seen during most of the year when the bars are developed best during or shortly after neap tides. It will be noted in figure 14 that the growth of the bars is also somewhat dependent on the small fluctuations between high low and low high tides.

Origin of Longshore-bars and Longshore-troughs

Speculation concerning the origin of longshore-bars has been appearing in print for more than a century. De Beaumont (1) first recognized these bars as a natural result of the readjustment of submarine slopes to existing wave conditions. He considered that wave action removed material from the sea floor and built it up as a bar parallel to the shore. Johnson (6) supported this hypothesis as the early stage in the origin of the emergent offshore bars. The present investigation, however, supports Evans (2, p. 510) in the indication that longshore-bars are in equilibrium with wave conditions and that the migration of the bars is only a temporary or seasonal fluctuation and does not form the broad emergent beaches to which the name offshore bar is applied.

Russell (12) and Gilbert (3) concluded from their studies of the longshore-bars of the Great Lakes that the materials of the bars were derived from the beaches and carried along the shore until deposited where the "undertow" loses its force. Evans (2, p. 503) supporting Johnson gave the following arguments against the origin by longshore currents:

> "1. Because of the acute angle at which the inner ball (longshore-bar) usually joins the shore
>
> 2. Because the ball (longshore-bar) does not receive any considerable amount of material from the locality where it joins the shore
>
> 3. Because of the failure of the ball (longshore-bar) to build above the water as does a spit or bar (bay bar)

4. Because of the lack of any considerable connection between the outer balls (longshore-bars) and the shore, although they are generally higher above the bottom and broader than ball No. 1 (innermost longshore-bar)

5. Because the line of the bottom of the lows (longshore-troughs) prolonged intersects the surface landward rather than seaward of the shore line."

The fifth point is significant since it indicates that erosion of the sea floor rather than simple deposition has taken place. However, it does not exclude longshore currents from an important part in the production of the longshore-bars. The other points depend on the assumption that longshore drift builds only structures which extend to the surface, such as spits, bay bars, and offshore bars. Actually there is no proof that this is the case.

One can agree better with Evans' suggestion (2, p. 508) that the longshore-troughs are the result of plunging breakers. However, his conclusion that the material set in suspension is carried out to form the bar may be only partially correct because the profiles along Scripps pier indicate that in many cases the material has come from the outside. Keulegan (7, figure 4) established through his experiments that the trough position is determined by the position of the plunging breaker. King and Williams (9, p. 80) considered that the bar forms at the "break point" as the result of seaward movement of material inside and landward on the outside.

The investigations at Scripps Institution do not offer any radically different hypothesis for the origin of the longshore-bars and longshore-troughs. The importance of the plunging of breakers is indicated by the close correspondence of the longshore-bar crest depths with the wave height. The waves steepen and start to break onto the bar and then plunge into the trough on the shoreward side of the bar. The position of the longshore-bar and longshore-trough is somewhat a matter of chance since given an even slope the position at which a series of newly developed large waves will break is dependent on the state of the tide when these waves begin their work. Many of the troughs may be initiated by the coincidence of several plunging waves along approximately the same line. Once developed the trough is likely to continue. Further indication of the importance of wave plunging in forming troughs and bars comes from the discovery that spilling waves such as accompany short-period storm waves with high local winds tend to obliterate longshore-bars. Under these conditions the longshore-bars and longshore-troughs at Scripps pier have been completely eliminated (figure 3, C) presumably because there was no breaker line. The inner longshore-bars and longshore-troughs are commonly destroyed by storm waves where the wind-driven waves break without plunging and no second set of breakers can be developed. This was nicely demonstrated by the effects of a northeast sorm which locally attained hurricane velocities along the outer side of Cape Cod, Massachusetts (figure 19).

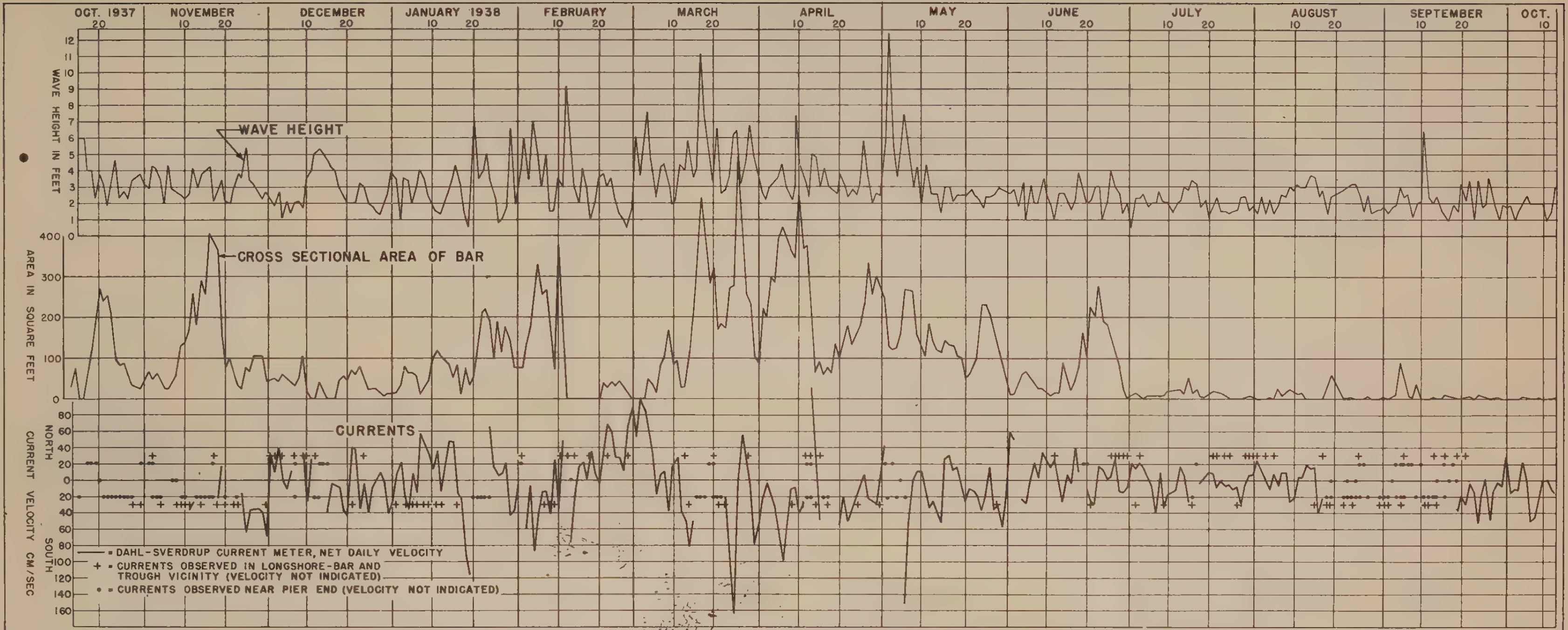
Longshore currents have an important influence in the development of longshore-troughs. The slight net seaward transport which is observed along the bottom inside the breakers tends to concentrate the bottom water in the longitudinal depressions produced by the plunging waves, resulting in a strong flow parallel to the shore. These currents become feeders to the rip currents which break seaward through the bar at various points (13). The channels along these feeder currents may be exposed at low tide. Isaacs found that the rippled inner troughs partially exposed by low tide deepened progressively towards a point where they connected with a passage leading through the bar (a rip channel).

According to measurements made by Scripps Institution groups along the southern California coast, the rip currents become concentrated in the surface layers outside the breakers with the result that there is no very definite indication of a seaward net transport of water along the bottom. Since shoreward velocities under wave crests are somewhat in excess of the seaward velocity under wave troughs, sediment tends to move shoreward along the bottom unless the slope is so steep that the gravitative effect will counteract this movement up the slope. The shoreward movement is of course most effective near the breaker line in the relatively shallow water where the wave effect is most vigorous.

If the wave height and the water level should remain essentially the same, a profile of equilibrium will result because the shoreward movement of the sand will build the bar up only to the height where waves will break on top of it with sufficient force to carry away the sand which is being added. Similarly the trough will continue to deepen only to the depth at which the bottom current is capable of carrying away the sand contributed to it both from the landward migrating bar outside the breakers and from the seaward transport of material inside the breakers.

If the wave height changes, the equilibrium will be disturbed. If the waves are larger (assuming the same period) the breakers will plunge on top of the bar and thus cut it away (figure 18, B) and after a time a new bar will develop seaward of the old (figure 18, C). In the early stages of large waves the cutting effect is the most significant but the sediment which is largely carried out in the rip channels will tend to be redistributed along the outer slope and start moving in to build up the bars at depths which are compatible with the new wave height. The few instances where deposition took place along Scripps pier during large waves are not clearly understood, but they are apparently the result of the reversal of current which caused a blocking of the natural outlets of the troughs and thereby caused an accumulation of the sediment against the pier.

Lowered wave height will allow the bar to grow shoaler and to encroach onto the trough as in figure 13, A-C. If the feeder currents are no longer capable of maintaining the trough in its deep position because of the shoreward movement of the breaker zone, the trough



VARIATION IN THE CROSS-SECTIONAL AREA OF THE LONGSHORE-BAR AT SCRIPPS PIER IN RELATION TO WAVE HEIGHT AND NEARSHORE CURRENTS

FIGURE 15

SEASONAL CHANGES OF LONGSHORE-BARS

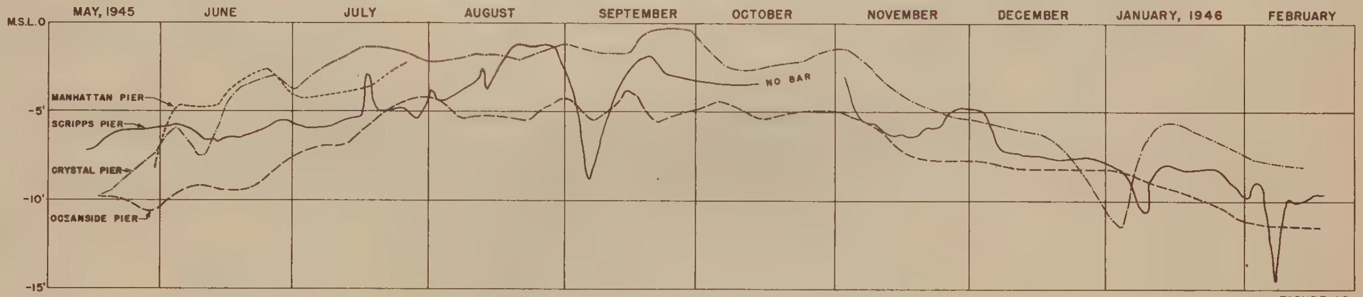


FIGURE 16

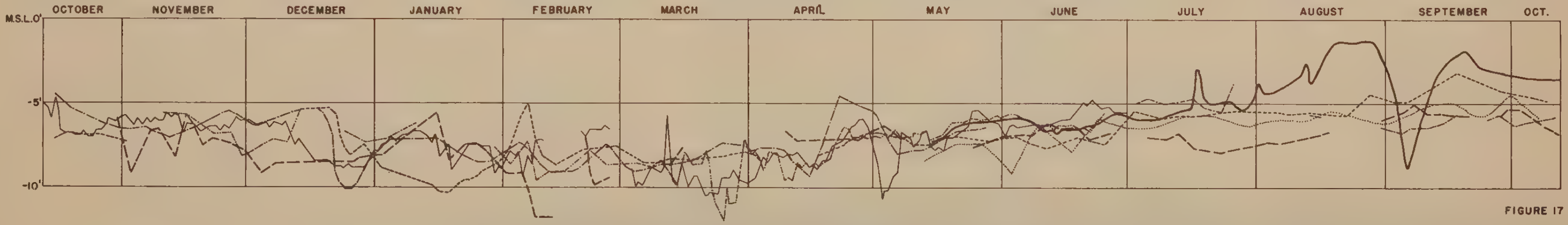
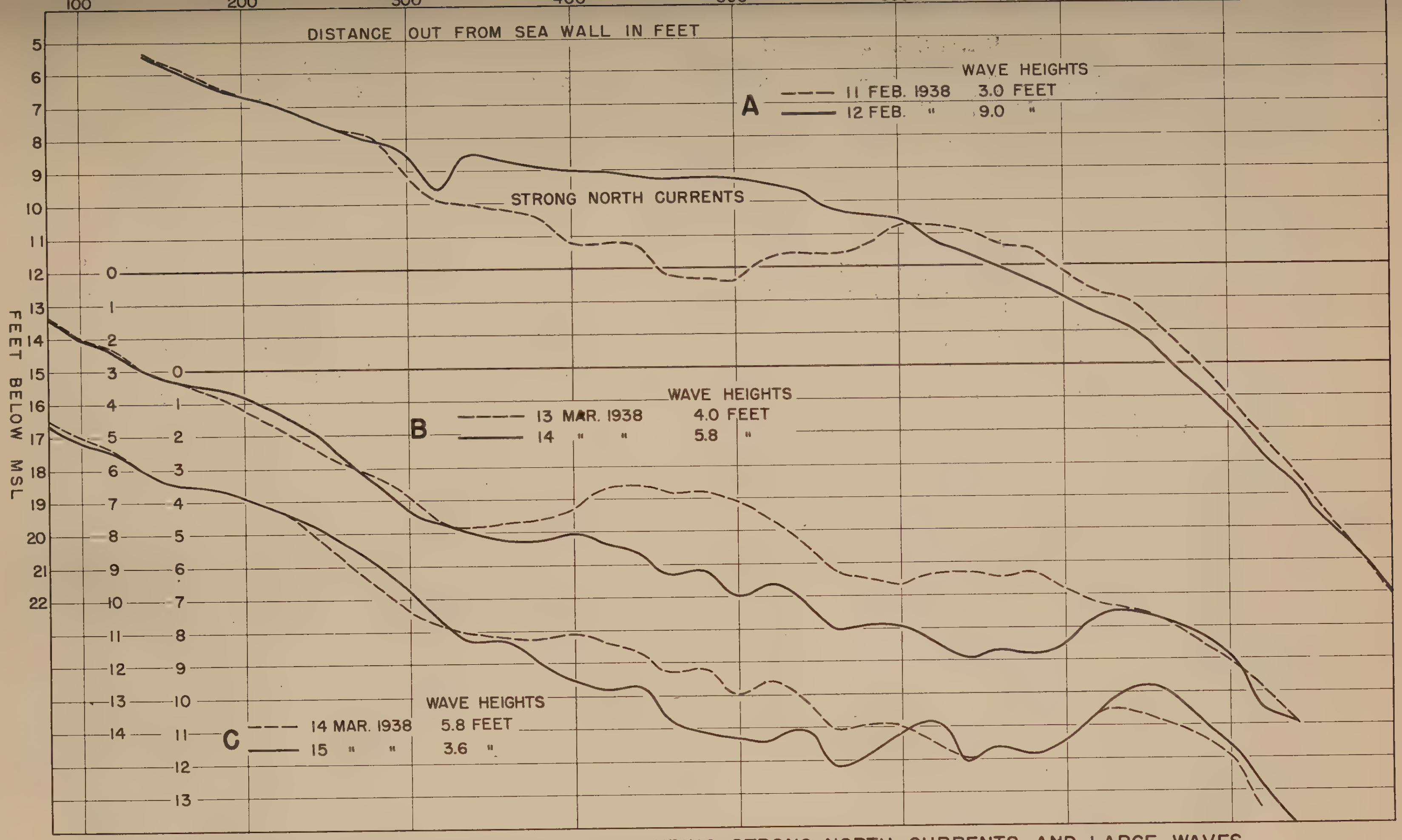


FIGURE 17

EIGHT YEARS OF SEASONAL CHANGES OF LONGSHORE-BAR AT SCRIPPS PIER



A - PROFILE CHANGES AT SCRIPPS PIER DURING STRONG NORTH CURRENTS AND LARGE WAVES
B - EXCAVATION AT SCRIPPS PIER DURING INCREASED WAVE HEIGHT
C - BUILDING UP OF BAR OUTSIDE AT SCRIPPS PIER DURING DECREASED WAVE HEIGHT

FIGURE 18

will fill and the slope become relatively even in the zone where the bar and trough had existed previously.

During periods of large waves the development of multiple longshore-bars is readily explained as the result of the re-forming of the waves over the troughs after breaking on the outer bar (figure 2). In shoaler water the wave breaks again with an exact repetition of the bar and trough forming process. Since the waves are smaller the topographic relief of the inner bars and troughs is less striking. Other cases of multiple bar development can be explained by a rising tide causing the waves to break at successively higher points along the slope. Wherever a good development of rip feeder currents is capable of carrying the sediment away from the plunge zone a trough will tend to develop. A falling tide, however, will tend to destroy the shoaler bars, as was shown in the tank experiments by King and Williams (9, p. 81). Longshore-bars and longshore-troughs developed by large waves may not be destroyed when the waves decrease and new bars and troughs are developed at shoaler depth. King and Williams developed two sets of bars in their tank experiments by decreasing the wave size. Isaacs found that during the small wave season he could anchor a wave meter on a deep outer bar off the Oregon coast and it remained undisturbed. These deep bars are the product of large winter waves.

The general absence of significant longshore-bars off steep beaches is readily explained by the fact that the waves break so close to the shore that there is no opportunity for the development of the longshore currents along the plunge zone. The association of well-developed cusps with these steep beaches is probably of some significance in this connection.

Summary and Conclusions

Slightly submerged sand bars extend parallel to the shore line off most gently sloping beaches. Hundreds of profiles of longshore-bars have been taken largely along the west coast. An analysis of these profiles has shown that there is considerable variation in the relation between depth of trough and depth of bar below mean sea level. The most representative relation shows that the troughs are 1.3 times as deep as the bars with reference to mean sea level, or 1.5 times as deep with reference to mean lower low water. The depth ratio between bar crest and bar base is 0.61 for mean sea level, or 0.55 for mean lower low water, which compares well with the 0.58 ratio indicated by Keulegan's experiments at the Beach Erosion Board laboratory. A source of difficulty in developing such ratios comes from the deepening of the longshore-troughs towards gaps in the longshore-bars.

The depth of the longshore-bars was found to be related to the height of waves and to the position of breakers. Plunging breakers excavate the bottom, producing the longshore-troughs. The material thus set into suspension is moved parallel to the shore by currents which turn seaward into rip channels forming gaps in the longshore-bars. Some of the bars and troughs are exposed by low tide. The

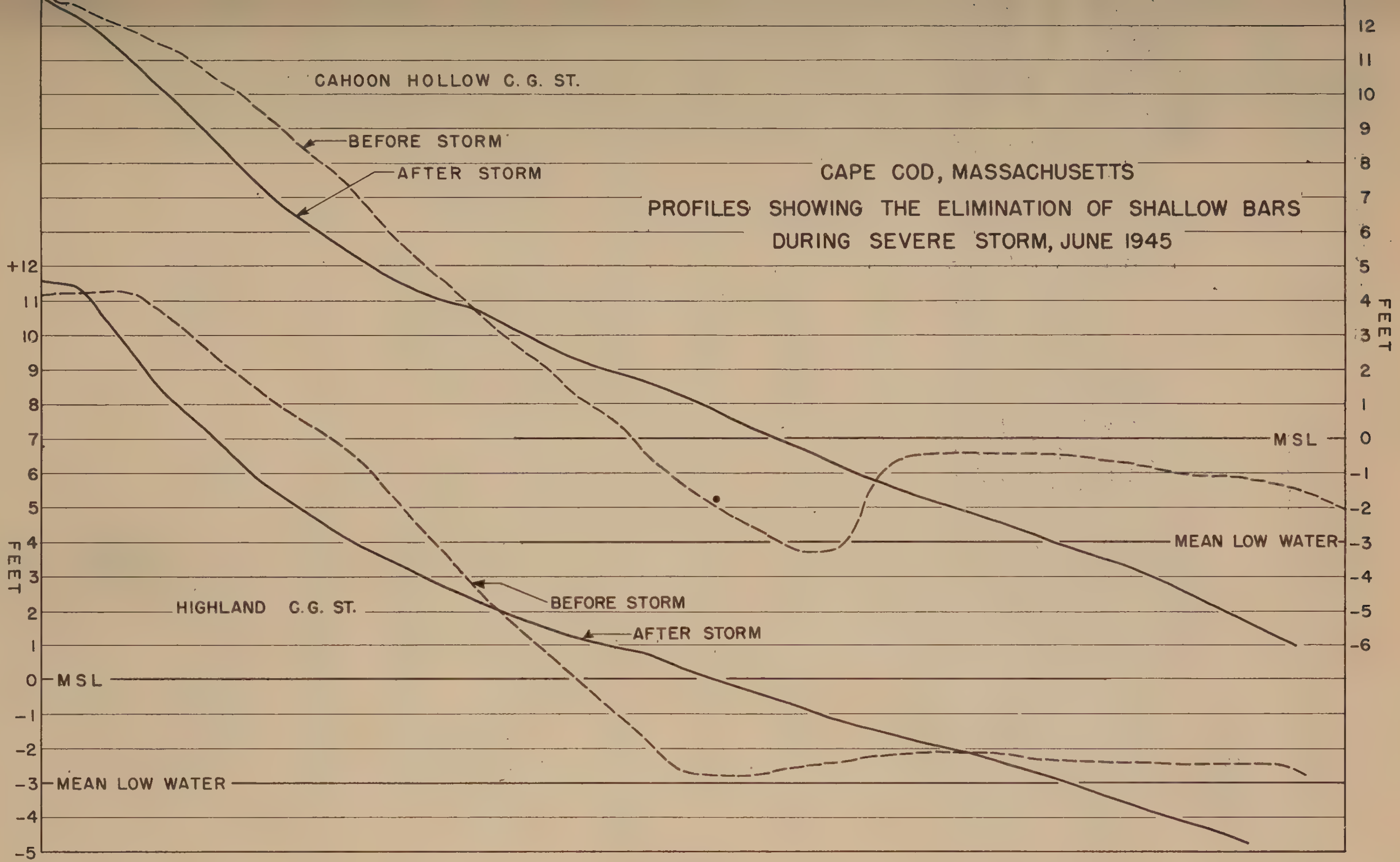

CAPE COD, MASSACHUSETTS
PROFILES SHOWING THE ELIMINATION OF SHALLOW BARS
DURING SEVERE STORM, JUNE 1945
CAHOON HOLLOW C. G. ST.
BEFORE STORM
AFTER STORM
HIGHLAND C. G. ST.
BEFORE STORM
AFTER STORM
MSL
MEAN LOW WATER
MSL
MEAN LOW WATER
FEET
+12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
FEET
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6

FIGURE 19

sand carried outside the bar is spread out over the slope by the expanding head of the rip current. Thence the shoreward drag under wave crests carries it back to build up the longshore-bars outside the troughs. The growth of these bars is limited by the depth at which the waves will plunge and prevent further sand encroachment.

Acknowledgments

The assistance received from U. S. Navy projects has been referred to previously. Expecial gratitude is expressed to E. C. LaFond who took many of the profiles along the piers, supervised the taking of a large part of the remainder, and was also a large contributor to determining the relations of the longshore-bars to the waves and currents. Much important information was contributed by John D. Isaacs from his extensive investigations of beaches along the west coast. Helpful suggestions were also provided by D. L. Inman and R. S. Arthur. Others who have taken an active part in the work include D. B. Sayner, Ruth Young, K. D. Langley, Ralph Gentoff, Mrs. Rosemarie Snow, and Mrs. Dorothy Williams.

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Contribution No. 455

ACCRETION OF BEACH SAND BEHIND A DETACHED BREAKWATER

TECHNICAL MEMORANDUM NO. 16
BEACH EROSION BOARD
CORPS OF ENGINEERS

MAY, 1950

Contribution from the Scripps Institution of Oceanography, New Series, No. 455

FOREWORD

This paper was prepared by John W. Handin of the University of California at Los Angeles and John C. Ludwick of the Scripps Institution of Oceanography. The report appeared in limited issue as Submarine Geology Report No. 8 of the Scripps Institution of Oceanography, University of California. It is believed that the results of the investigations outlined herein are of sufficient value to merit publication at this time.

The opinions and conclusions expressed by the authors are not necessarily those of the Board.

The authority for publication of this report was granted by an act for the improvement and protection of beaches along the shores of the United States, Public Law No. 166, 79th Congress, approved July 31, 1945.

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CCRETION OF BEACH SAND BEHIND A DETACHED BREAKWATER

ABSTRACT

The problem of sand transport by a longshore current is clarified by observing the effect of a breakwater on this current.

Sand samples were collected on a network from the beaches in the vicinity of the breakwater at Santa Monica, California. The distribution of median grain sizes is evidence for a reduction of the competence of the longshore current. The history of shore line changes discloses an accompanying reduction in the capacity of the current. A decrease in transporting power of the longshore current is correlated with a decrease in Q, the littoral drift factor, so that Q can probably be used as a qualitative measure of the sand transporting power of longshore currents.

The history of accretion indicates that a shore line changes position in a direction toward equilibrium with respect to the forces acting on a beach. Given enough time, it is probable that the breakwater will become connected to the mainland.

Introduction

A beach system is in equilibrium when there is a balance between sand supply and erosion such that the volumes of material entering and leaving the system are just equal. If the rate of erosion is greater than the rate of supply, a beach retrogrades, and if the rate of erosion is less than the rate of supply, a beach progrades. The detached breakwater, constructed at Santa Monica, California, in 1933-34 (figure 1), decreased erosion and caused accretion in the lee of the breakwater.

The Santa Monica Municipal Pier is located at a point on the shore between the headlands of Santa Monica Bay. Upcoast from the pier the shore line extends 3 miles to the northwest, thence more than 30 miles to the west. Downcoast from the pier the shore line extends about 15 miles in a southeasterly direction to Rocky Point (figure 2). Of rubble stone construction, the breakwater is 2,000 feet long with its southern end directly seaward of the pier. Originally the breakwater was 2,000 feet offshore and oriented parallel to the shore line (approximately northwest-southeast).

Investigations of the breakwater and adjacent beaches have been made by A. G. Johnson(5,6) of the Los Angeles City Engineer Office, and by the Los Angeles District, Corps of Engineers(2). Grant and Shepard(4) published a paper on shallow-water sediment-shifting processes which included a discussion of sedimentation behind the breakwater. J. W. Johnson(7) made a model study of accretion behind the breakwater.

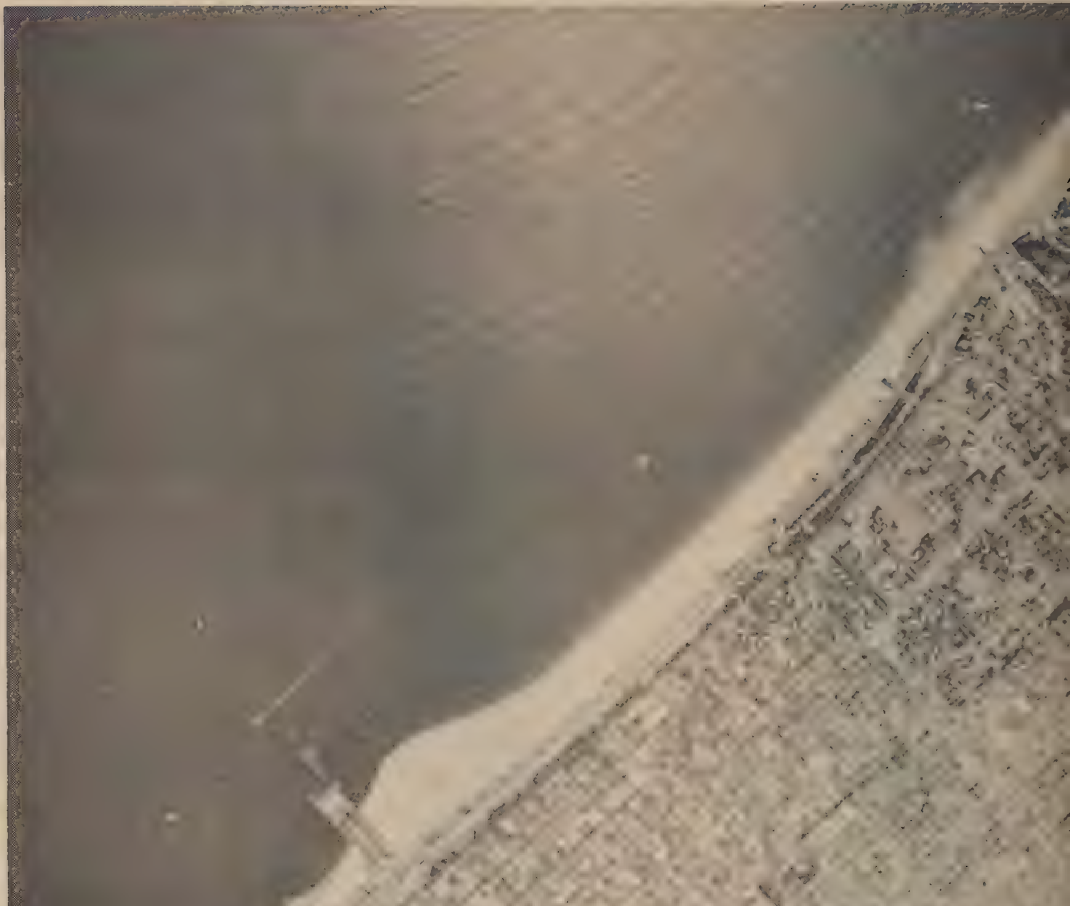

FIGURE I. AERIAL VIEW OF SANTA MONICA BAY, JUNE 22, 1947, SHOWING ACCRETION OF BEACH SAND BEHIND SANTA MONICA BREAKWATER.

(PHOTO BY FAIRCHILD AERIAL SURVEYS, INC.)

The history of accretion at Santa Monica is disclosed by successive positions of the shore line (figure 3). The purpose of this investigation is to interpret this history in terms of the physical processes which are involved, including wave erosion and transportation of sand by longshore currents. The effect of the bottom topography and the breakwater on wave diffraction and refraction is indicated by diagrams based on diffraction and refraction theory(9,12). Textural variations of the beach sands are used to test the theories.

The General Environment

The beach sand at Santa Monica is derived from the southern slopes of the central and western Santa Monica Mountains and probably in part from the beaches northwest of the mountains. The source rocks are sandstones, shales, conglomerates, and basic volcanics. Streams draining the mountains are short, intermittent, and have steep gradients. When rainfall in the mountains is of high intensity the streams become torrential. Since orientation of the shore line is such that approaching wave induce a net southerly current, sediment is moved by longshore currents downcoast to the Santa Monica beaches from the points where the streams debouch into the sea(2).

Wave trains that reach the southern California coast with sufficient energy to move sand can be classified as to source into three categories: swell from the North Pacific, arriving with deep-water heights of 3 to 6 feet and periods of 6 to 19 seconds; swell from the southern hemisphere with heights of 1 to 4 feet and periods of 15 to 20 seconds; and swell from a nearby generating area 75 to 100 miles offshore, arriving with heights of 4 feet or more and periods of 5 to 7 seconds. Less frequently, high wind waves are generated by local storms. These wind waves can approach from almost any direction between southeast and northwest and attain heights of 10 feet or more(2). The waves which occur most frequently are so refracted that they approach approximately normal to the breakwater axis.

Sampling and Laboratory Procedure

A network of sampling points was laid out so that certain groups of points would be located over old beach zones. In order to lay out the network in this fashion the location of the old shore lines had to be ascettained from previous surveys of the Santa Monica beaches (figure 3).

At each sampling point other than on the foreshore approximately 500 grams of sand were collected from a pit about three feet deep which was dug to penetrate the upper wind-drifted sand. The samples therefore are probably more representative of the underlying old-beach material. Local sorting differences were largely eliminated by collecting intergrated samples from a 6-inch stratigraphic interval at the bottom of the pit. Samples collected from the foreshore were taken at points located midway between the edge of the water and the crest of the berm, and were collected from the surface because of the presence of very coarse sand

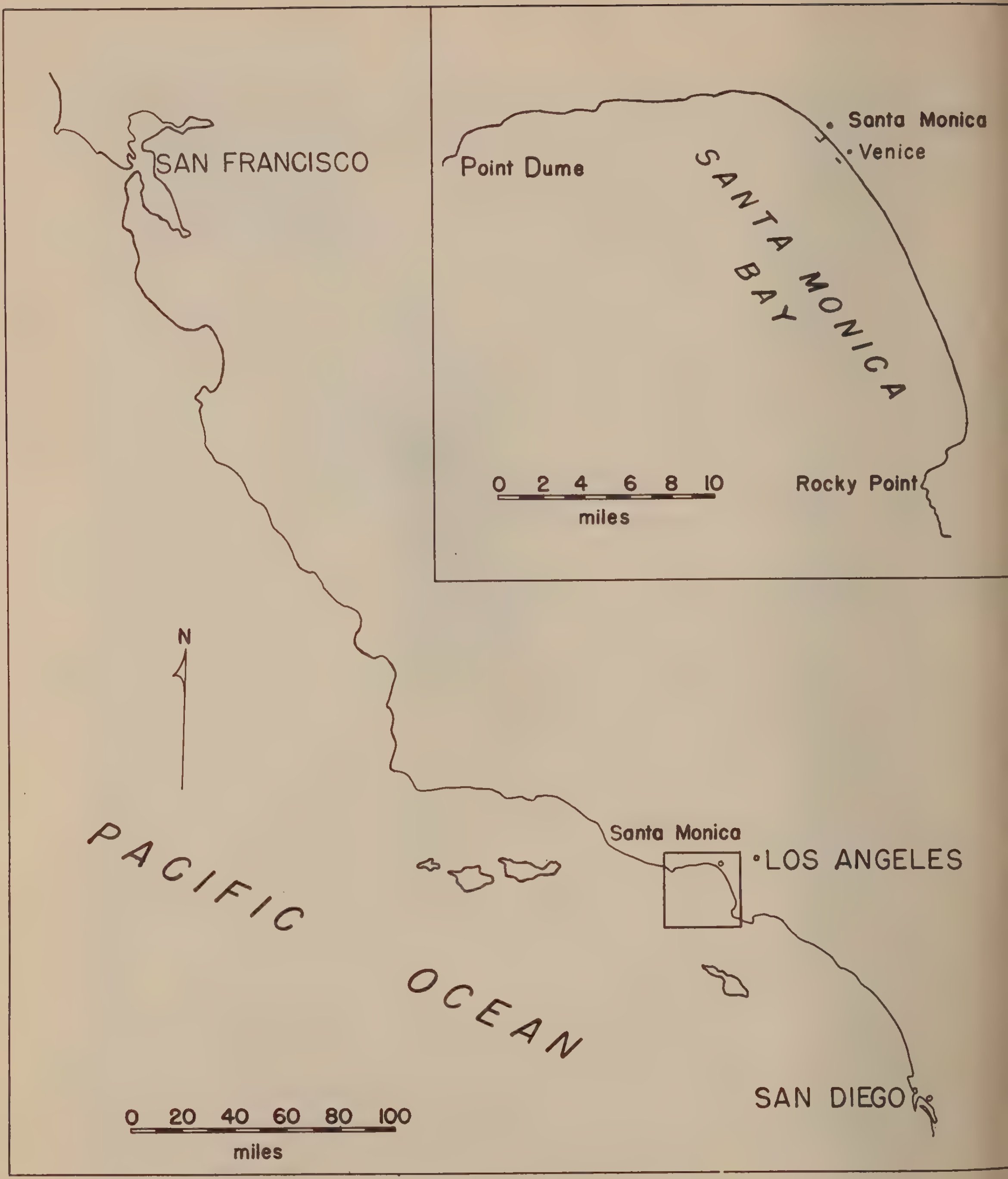
Santa Monica
Venice
Point Dume
SANTA MONICA BAY
0 2 4 6 8 10
miles
Rocky Point
SAN FRANCISCO
N
PACIFIC OCEAN
Santa Monica
LOS ANGELES
SAN DIEGO
0 20 40 60 80 100
miles

Figure 2

INDEX MAP

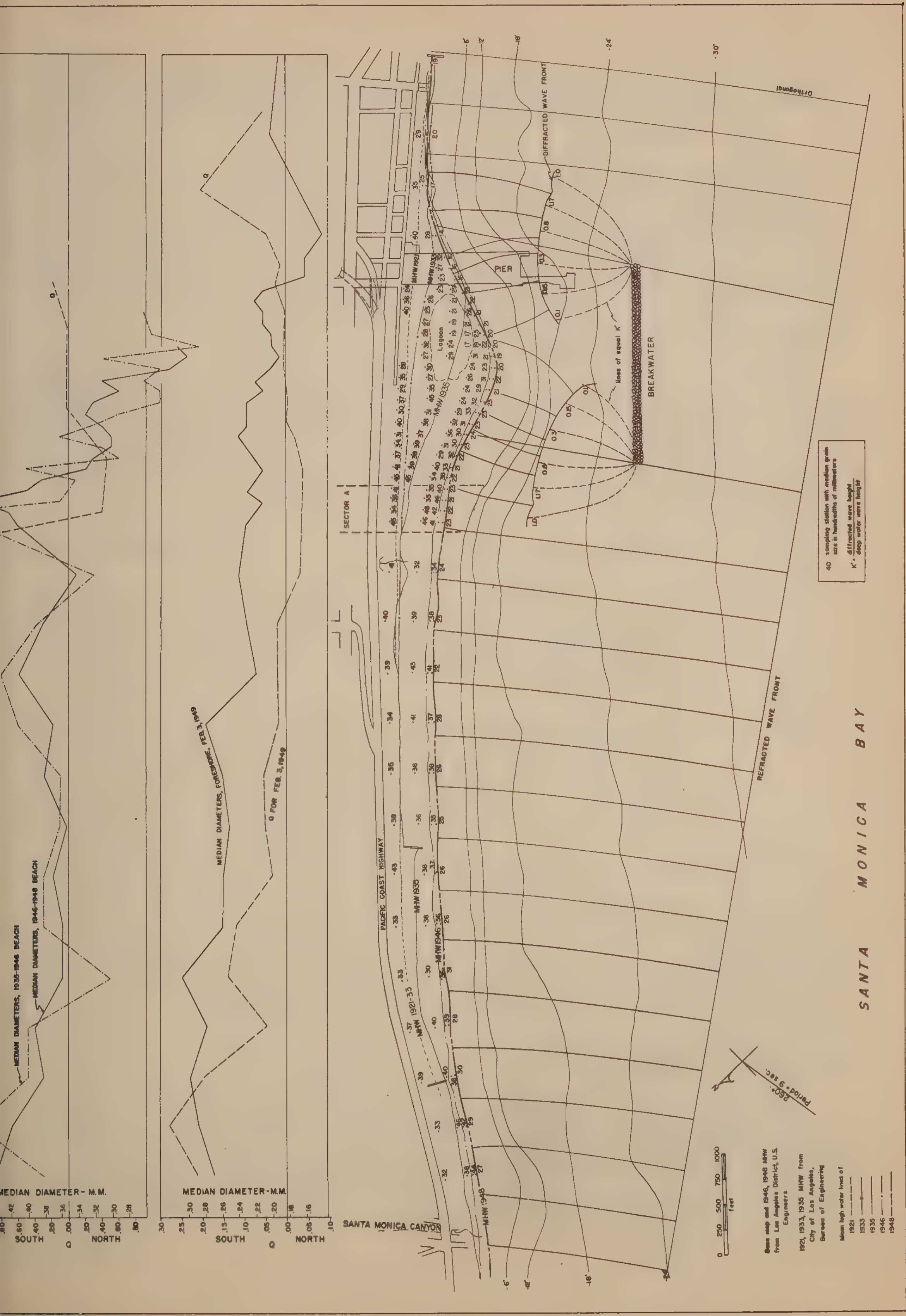
MEDIAN DIAMETER - M.M.
SOUTH
Q
NORTH
MEDIAN DIAMETERS, 1935-1946 BEACH
MEDIAN DIAMETERS, 1946-1948 BEACH
MEDIAN DIAMETER-M.M.
MEDIAN DIAMETERS, FORESHORE, FEB. 3, 1949
Q FOR FEB. 3, 1949
SANTA MONICA CANYON
PACIFIC COAST HIGHWAY
SECTOR A
PIER
Lagoon
MHW 1921
MHW 1933
MHW 1935
MHW 1946
MHW 1948
MHW 1921-33
BREAKWATER
lines of equal K'
DIFFRACTED WAVE FRONT
REFRACTED WAVE FRONT
Orthogonal
SANTA MONICA BAY
260°, Period = 9 sec.
40 sampling station with median grain size in hundredths of millimeters
K' = diffracted wave height / deep water wave height
Base map and 1946, 1948 MHW from Los Angeles District, U.S. Engineers
1921, 1933, 1935 MHW from City of Los Angeles, Bureau of Engineering
Mean high water lines of
1921
1933
1935
1946
1948
0 250 500 750 1000
feet
-6'
-12'
-18'
-24'
-30'

FIGURE 3

immediately beneath the surface layer. Such samples were collected by scooping up the surface layer from an area of several square feet. This technique was employed to collect material deposited by waves occurring at the time of sampling.

Samples were sun-dried and split to three grams using a Jones sample splitter. Median diameters were determined by using an Emery settling tube(3). This method is more rapid than seiving and probably comes closer to duplicating natural conditions of sedimentation. Values are expressed to only two significant figures because the combined experimental and "sampling" probable error is on the order of 5 per cent(8).

History of Shore Line Changes

Prior to construction of the breakwater, the Santa Monica shore line had been comparatively stable since the earliest reliable surveys(14), with the exception of a moderate advance near the Santa Monica Municipal Pier. In 1933, immediately after construction was undertaken, the shore line behind the breakwater began to advance. Successive positions of the mean high water line are shown in figure 3.

Significant facts of the shore line changes include the following:

1. The point of maximum advance of the 1935 shore line is approximately opposite the southeast end of the breakwater. There has been a progressive northward shift of the salient to the present position opposite the center of the breakwater.

2. The 1935 shore line joins the pre-breakwater shore line at a point just beyond the north end of the breakwater. Subsequently, prograding has occurred farther and farther to the north. In 1948, the beach was prograding at a point two miles north of the breakwater.

3. Between 1946 and 1948 the shore line immediately southeast of the salient receded.

During the history of accretion, the offshore contours advanced roughly parallel to the advancing shore line so that the offshore slope remained constant. There has been no appreciable change in the position of the 24-foot depth contour.

Texture of the Beach Sands

Median diameter of the sand at each sampling point is plotted in figure 3. Maximum, minimum, and average values of median grain size for each beach zone are tabulated in table 1. During 1939 and 1940, dredging on the prograded beach behind the breakwater produced a shallow lagoon. Dredgings were pumped to a point on the beach 900 feet southeast of the pier. After operations were discontinued the lagoon filled with fine sand. Median diameters of sand samples collected from the lagoon were not included in computing values in table 1.

TABLE 1

Summary of Beach Sand Grain Sizes of
Samples Collected on 3 February 1949

Beach Zone	Median Diameters in mm.			
	Max.	Min.	Average	
Pre-breakwater zone (pre-1933)	0.45	0.24		0.36
1933-1935 zone	.45	.23		.32
1935-1946 zone	.48	.19	North of sector A: South of sector A:	.39 .29
1946-1948 zone	.46	.21	North of sector A: South of sector A:	.37 .30
Foreshore Feb. 3, 1949	.31	.14		.23

Significant facts of the beach material as shown by figure 3 and table 1 include the following:

1. There is a random distribution of median diameters of the sands of the pre-breakwater beach.
2. On subsequent beaches the distribution of median diameters indicates that a variation series exists(11).
3. On the beach built between 1933 and 1935, the coarsest sand occurs at the north, and there is a decrease in grain size to the south. Finer sand occupies the site of the lagoon.

4. The samples which represent the 1935-1946 and 1946-1948 beaches show a random distribution of median diameters upcoast from Sector A (the area of maximum median grain size, arbitrarily designated Sector A for convenience in reference, see figure 3). There is an abrupt increase in grain size within Sector A, but downcoast there is a gradual decrease. To the north of Sector A, the average median grain size is greater than it is to the south.

5. On the foreshore of 3 February 1949, median diameters gradually decrease from Santa Monica Canyon to the pier.

Discussion

The Corps of Engineers has been making use of the littoral drift factor, Q, in studies of littoral transport in southern California. The Corps acknowledges that the validity of the equation relating sand transport to littoral forces has not been proved through field investigations or model studies. However, the Corps considers the analysis of Q factors, as computed by this formula, the most satisfactory theoretical approach to the correlation of littoral drift and its generating forces thus far derived. According to the Los Angeles District, Corps of Engineers(2) Q is defined as:

$$Q = k\,w\,e\,\sin 2\alpha$$

where

Q = littoral drift factor-total amount of sand moved in littoral drift past a given point on the shore in one year by waves of a given period and direction.

w = wave work factor, total work done by all waves of a given period and direction during an average year.

e = relative wave energy per unit length of wave crest

$$= \frac{\text{shallow-water wave energy}}{\text{deep-water wave energy}}$$

α = angle between a wave crest and the shore line or between an orthogonal and the normal to the shore line. The angle opens in the direction of the longshore current.

k = a factor depending on dimensions, and a number of unevaluated variables such as bottom slope and roughness.

Owing to the unknown magnitude of k, only relative values of Q may be computed for points on the beach. Thus for comparative purposes, k is assumed to be constant and assumed to be unity. It is assumed that wave work (energy) is the important parameter in measuring the rate of littoral drift. The deep-water wave work, w, must first be converted to wave work in the breaker zone by multiplying by the coefficient e. The longshore component of this work at a point on a wave crest is calculated by multiplying by $\sin \alpha$. It is then multiplied by $\cos \alpha$ to obtain the total longshore component of the work along the wave crest. ($\sin \alpha \cos \alpha = \frac{1}{2} \sin 2\alpha$).

Plotted on figure 3 is a combined refraction and diffraction diagram for waves prevailing at the time of sampling. The wave period and height were observed. The deep-water wave direction (260°) was assumed to be the most likely direction for waves of the observed period (9 sec.) and height (1 foot) occurring at this time of year(10). Wave refraction methods as described by Munk and Traylor(9), and wave diffraction as developed by Putnam and Arthur(12) were utilized.

Values of Q at several points on the shore were computed using values of e and α measured from figure 3. The coefficient of energy, e, is calculated by taking the ratio of the distance separating orthogonals in shallow water to the distance separating orthogonals in deep water. The work factor, w, has been calculated for various periods and directions(13). This factor, w, has the value 0.75 for the waves that were obtained on the day of sampling. The values of Q are plotted (figure 3) as a function of distance along the beach. An additional set of values of Q, kindly furnished by J. W. Dunham of the Los Angeles District, Corps of Engineers, is also plotted. These values are algebraic sums of Q determined for waves of all probable periods and directions of approach during an average year. Only one value of the average annual Q is available for the entire shore line between the breakwater and Santa Monica Canyon.

A comparison of the plots of median diameter of the foreshore sands and Q, shows that a decrease in Q is accompanied by a decrease in grain size. Inasmuch as Q is a function of the longshore component of the energy content of the waves, it is reasonable to suppose that competence and capacity of the longshore currents decrease with decreasing values of Q. With the progressive decrease in capacity southward there is progressively more deposition, and with the southward decrease in competence there is a progressive decrease in grain size. The finest sand on the foreshore, however, occurs at a point south of the breakwater and not at the point of minimum Q. The reason for this is that only the finest sand can be moved through the zone of minimum wave action at the salient, with the result that the source for the downcoast beaches is limited to the finest sand.

Since Q increases from the point of the salient southward, but the source of sand is insufficient to balance the increase wave erosion, the zone immediately south of the pier is one of erosion. If no sand passed the salient, the sand in this erosion zone would be coarse-grained since the finer sand would be removed first from whatever beach existed there. It seems probable that fine sand is deposited during times of low waves and the beach is eroded during times of high waves.

In Sector A there is an abrupt increase in mean grain size for the older beaches (1935-1946, 1946-1948, in figure 3) but the average annual Q shows a marked decrease. The explanation for this is believed to be that only the finer part of the sediment load can be transported through the zone of reduced wave turbulence. The coarser part is dropped resulting in an increase in median grain size. South of Sector A grain size decreases with Q and the minimum grain size corresponds to the minimum value of Q.

The average texture of the older beach sands is coarser than that of the foreshore sands, because the height of the wave prevailing at time of sampling was less than average. Handin's weekly observations over a period of one year at the mouth of Santa Monica Canyon indicate that the average annual wave height is 2.8 feet. On the day of sampling the wave height at this point was only 1 foot.

A breakwater creates what has been called a "wave shadow" (4, p.804) in its lee. Actually, approaching wave fronts are diffracted around the ends of the breakwater. The diffraction patterns in figure 3 indicate that all points on the shore receive some wave energy and that the reduction in wave energy is effective outside the limits of the breakwater. Since the refracted waves approach approximately normal to the breakwater most of the time, the point of minimum wave energy on the shore is usually opposite the center of the breakwater.

Construction of the breakwater began at the south end; accordingly the site of initial accretion was near the pier. At first, accretion resulted because of reduced wave turbulence. At some later time the configuration of the shore line was such that there was a tendency for the wave fronts to produce local reversal in the direction of the longshore current immediately north of the salient. Thereafter, the effect of the breakwater, or more directly, the effect of the projecting accretion has been essentially the same as that produced by a groin.

The effect of this tendency for a local reversal in the direction of the longshore current is to decelerate the dominently south-flowing current. However, the amount of retardation in the "zone of reversal" is not sufficient to reduce the velocity of the current to zero. Thus some fine sand is transported downcoast beyond this zone and even beyond the salient. Probably there is no "zone of reversal;" the direction of the current is determined from refraction and diffraction diagrams which indicate only theoretical values and do not necessarily represent the details of the actual current pattern. For example, no allowance is made for the existence of random eddies (rip currents) in the flow, nor is any check made in computing the longshore flow to see whether the requirements of continuity are satisfied. In the case at hand, the width of the surf zone immediately north of the "zone of reversal" is greater than the width south of it. This cross-sectional area of the currents associated with these two zones reflects the difference in width. Thus it seems probable that the larger volume of south-flowing water masks the apparent tendency for a north-flowing current which really exists only as a retarding effect.

With the completion of the breakwater, the point of maximum accretion migrated northward in response to the shift in the location of the point of minimum wave energy. As accretion progressed the projecting shore line became a more effective barrier to littoral drift and more sand was deposited on the upcoast beaches. Although the rate of advance of the shore line at the salient has decreased, the rate of total accretion has remained fairly constant. The volume of sand added each year is simply distributed over a greater distance along the shore.

Given enough time, the beaches will become stabilized along a new equilibrium alignment for the average wave conditions and the average rate of supply of detritus. At the present time, unbalanced factors in this environment continue to cause shore line changes in a direction toward the equilibrium position.

For example, the equilibrium position for the shore line of the upcoast beach is parallel to the pre-breakwater beach on a line in prolongation of the breakwater axis. Thus the upcoast beach is prograding toward this new stable shore line. If the salient ultimately reaches the breakwater, this beach will prograde rapidly and the littoral drift will bypass the breakwater and replenish the sand-starved beaches to the southeast.

By analogy to optics, a detached breakwater is probably an effective barrier to waves if it is no longer than one wave length. When the length of breakwater is only a fraction of its distance offshore, diffracted and refracted wave crests have enough distance to turn through at least one quadrant, thereby propagating wave energy sufficient to maintain sand in suspension and transit behind the breakwater. In this case equilibrium is attained before the salient reaches south of Santa Monica. At Venice, California, a shore line of equilibrium was established before the accretion reaches the breakwater. Originally this structure was about the same distance offshore as the Santa Monica Breakwater, but it is only about 600 feet long. Recently an artificial beach was built to within about 500 feet of the breakwater. Waves rapidly constructed a tombolo.

Left to itself, the Santa Monica Breakwater which was the same distance offshore but is longer than the Venice Breakwater, will probably become connected to the mainland.

Summary and Conclusions

The study of sand accretion behind the detached breakwater at Santa Monica furnished several conclusions pertinent to an understanding of littoral processes.

1. A beach system is in equilibrium when there is a balance between sand supply and erosion such that the volumes of material entering and leaving the system are just equal. If an unbalance is created by the introduction of a disturbing element into the system, ensuing changes in the system proceed toward a new equilibrium position.

2. A detached breakwater is a disturbing element if it is at least one wave length long and if it is close enough to shore to produce an appreciable reduction of wave energy in the surf zone.

3. Median grain size of the beach sand was used as an indication of longshore current competence. A correlation was found between grain size and Q, the littoral drift factor, which suggests that competence varies directly with Q.

4. The rate of accretion was used as an indication of longshore current capacity. There is a correlation between rate of accretion and Q which implies that capacity varies directly with Q.

5. The evidence from Santa Monica breakwater would seem to verify the assumption made regarding the sand transporting power of longshore currents(13), that wave energy is a more important parameter than wave height. In additional, this evidence confirms, in true scale, the results of model experiments which previously indicated a relation between sand movement and wave work(14). Finally, the evidence indicates that the littoral drift factor is probably justified as a qualitative measure of the transporting power of the littoral currents, since both competence and capacity of the longshore currents appear to vary directly with Q.

Acknowledgments

Thanks are especially due J. W. Dunham for cooperation throughout the preparation of this paper. R. S. Arthur was very helpful with problems of wave diffraction. The authors are indebted to Professor F. P. Shepard for his critical reading of the manuscript.

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Contribution No. 456

LONGSHORE CURRENT OBSERVATIONS IN SOUTHERN CALIFORNIA

TECHNICAL MEMORANDUM NO. 13
BEACH EROSION BOARD
CORPS OF ENGINEERS

JANUARY, 1950

Contribution from the Scripps Institution of Oceanography, New Series, No. 456

FOREWORD

This paper was prepared by Dr. Francis P. Shepard of the Scripps Institution of Oceanography. The report was first published in limited issue by the Scripps Institution of Oceanography, University of California. It is believed that the findings of the investigations outlined herein are of sufficient value to merit publication at this time.

The opinions and conclusions expressed by the author are not necessarily those of the Board.

The authority for publication of this report was granted by an act for the improvement and protection of beaches along the shores of the United States, Public Law No. 166, 79th Congress, approved July 31, 1945.

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LONGSHORE CURRENT OBSERVATIONS IN SOUTHERN CALIFORNIA

Abstract

Under Navy contract N6ori-111 at Scripps Institution of Oceanography currents were measured in the surf zone at frequent intervals throughout a year at a series of stations along the southern California coast from the Mexican border to Newport. The study of the data from these measurements shows that the dominant currents in the area are to the south, evidently in response to the direction of approach of the principal wave trains. North currents indicative of southern hemisphere storms prevail during a large part of the summer and fall. The feeders of rip currents were found to be important causes of longshore currents, particularly in areas with considerable submarine relief, but also in areas with straight beaches and parallel contours. Strong longshore currents exist even during times when large waves approach with their orthogonals essentially normal to the beaches. The importance of currents moving along the shore away from points of wave convergence was demonstrated by the year's investigation and has been confirmed subsequently by studies in the La Jolla area.

Introduction

During the war an attempt was made by Munk and Traylor (2) to determine the longshore currents in the surf zone which were induced by the diagonal approach of waves to the coast. By combining observations largely at Oceanside, California, with a theoretical study of the various parameters, a working hypothesis was evolved for the prediction of longshore currents from wave forecasts. This work has since been extended with laboratory experiments and extensively revised (4). While the current measurements in the present report may provide some check on these methods, they were carried on largely for the purpose of finding the predominant direction and seasonal variations in sand drift along the shore at a number of beaches, at most of which seasonal sand changes had been observed previously. It was hoped also that the analysis of a large body of data taken at intervals of about 12 days over a period of a year might throw additional light on the following problems.

1. The effect of breakwaters on beaches

2. The effect of various types of submarine topography on longshore currents

3. The relation of the currents to projecting points of land

4. The relation of longshore currents to such parameters as breaker height, slope of beach, wave period, and angle of incidence.

5. The relation, if any, of the tides to longshore currents on open coasts.

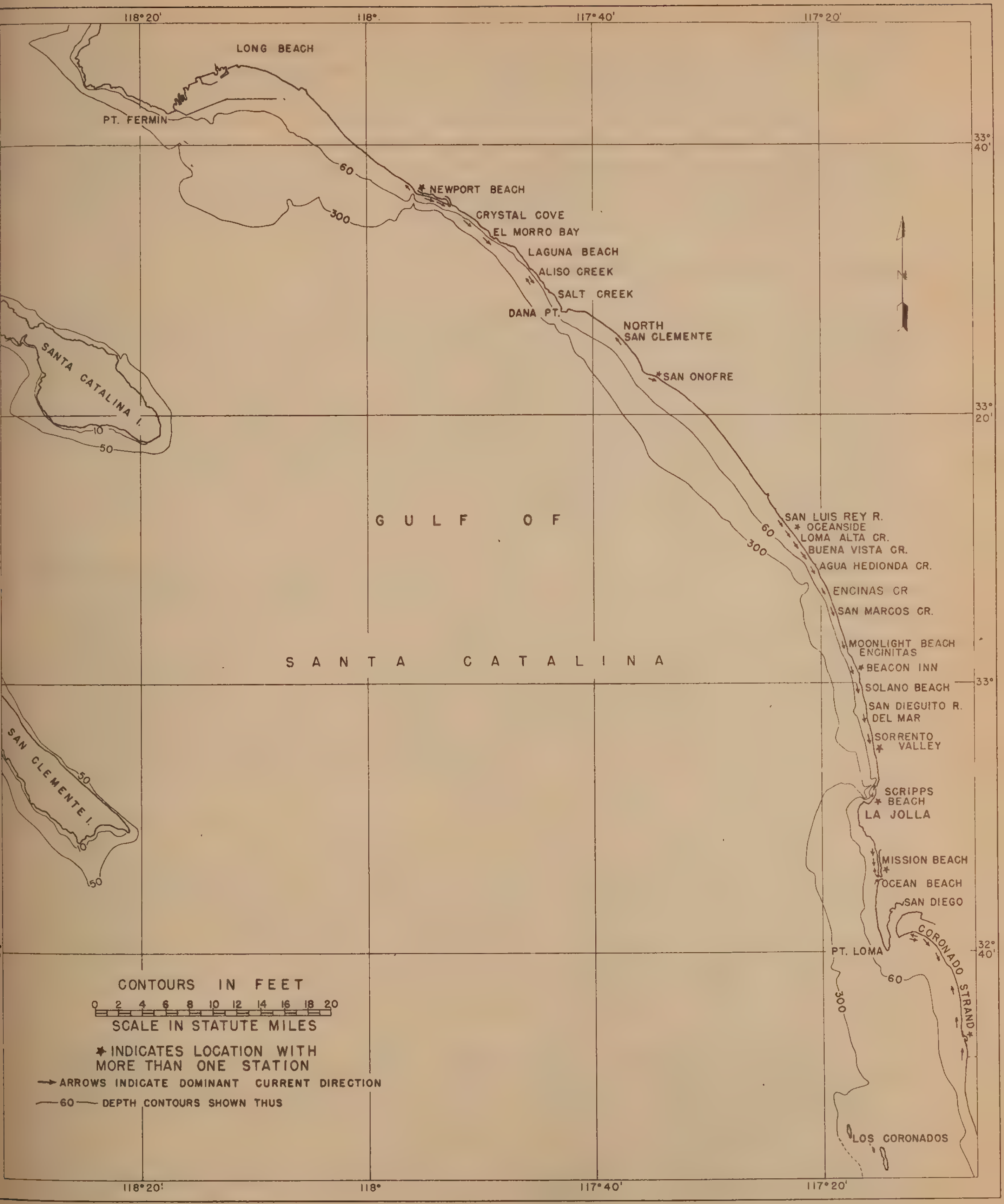
The observations were obtained at 63 stations extending for 100 miles from the Mexican border to Newport, California (Figure 1). The stations are at varying distances one from the other depending largely on expediency of observation. Thus, in the vicinity of Scripps Institution there were 18 stations, separated by only a few hundred feet. On other beaches the stations were separated by a matter of one or more miles. On 11 beaches only one point was readily accessible so that currents were observed at that point only.

The data obtained at stations included the following: average current velocity and direction measured by drift bottles, height of breakers during the operation, direction of approaching breakers, wave periods, and water temperature. The data were obtained at an average depth of $2\frac{1}{2}$ feet. Observations were also made on berm widths, cusps, and on any other special beach phenomena. In the report, data obtained over a number of years at local beaches is also considered.

The various beaches where observations were made are considered separately including a description of the areas and the special features and influences observed. The descriptions are made from south to north, partly because of the very special situation which exists at the northernmost beach.

Methods of estimating net drift and net transport. - It might be supposed that with the large number of observations it would be relatively easy to estimate the net drift along the shore and the net direction of sand movement at each beach, but actually there are numerous complications. Simply taking the number of observations north and the number south and comparing the totals tells little of itself since obviously there might be 10 times as much movement observed in one direction at one-tenth the velocity so that the water movement would be equal. Also the movement could occur over a broad surf zone at one time and a narrow zone at another. So far as sand transport is concerned, the size of breakers plays an important part since the larger the breakers the more sand is held in suspension for transportation by the currents. Therefore with large breakers it is possible for transport to be increased a thousandfold over the transportation of small breakers. Similarly, sand transport increases as an exponent of the current velocity.

In order to evaluate the effect of stronger currents, it is possible to multiply the average current for north and south by the number of north and south observations. In trying to estimate the sand transport it seemed advisable to use some exponent of both the current velocity and the height of breakers. An exact amount to use was impossible to estimate since unknown factors enter the picture. However, it was thought that some approximation could be reached by multiplying the square of the breaker height by the square of the velocity. The results proved to be somewhat


118°20'
118°
117°40'
117°20'
33° 40'
33° 20'
33°
32° 40'
LONG BEACH
PT. FERMIN
60
300
NEWPORT BEACH
CRYSTAL COVE
EL MORRO BAY
LAGUNA BEACH
ALISO CREEK
SALT CREEK
DANA PT.
NORTH SAN CLEMENTE
SAN ONOFRE
SANTA CATALINA I.
10
50
N
GULF OF SANTA CATALINA
SAN LUIS REY R.
OCEANSIDE
LOMA ALTA CR.
BUENA VISTA CR.
AGUA HEDIONDA CR.
ENCINAS CR
SAN MARCOS CR.
MOONLIGHT BEACH
ENCINITAS
BEACON INN
SOLANO BEACH
SAN DIEGUITO R.
DEL MAR
SORRENTO VALLEY
SCRIPPS BEACH
LA JOLLA
MISSION BEACH
OCEAN BEACH
SAN DIEGO
PT. LOMA
CORONADO STRAND
LOS CORONADOS
SAN CLEMENTE I.
CONTOURS IN FEET
0 2 4 6 8 10 12 14 16 18 20
SCALE IN STATUTE MILES
* INDICATES LOCATION WITH MORE THAN ONE STATION
→ ARROWS INDICATE DOMINANT CURRENT DIRECTION
—60— DEPTH CONTOURS SHOWN THUS

LOCATION OF MEASUREMENT STATIONS AND DIRECTIONS OF PREDOMINANT LONGSHORE CURRENTS

FIGURE 1

questionable because the figure for one unusual day of observations can outbalance the sum of all the rest. For this reason the computations will not be included here but use of them was made in constructing the maps which give directions and relative amounts of drift. From any study of this kind one is bound to end with the conviction that there are so many unknowns that one is left in a hopeless tangle of inadequate observations and inadequate means of comparison. Nevertheless, the results appear to have some meaning and some consistency one with the other which appear to justify the study.

Causes of Longshore Currents

Probably the most important cause of longshore currents is the angle of incidence of wave orthogonals to the shore. As has been shown by Munk and Traylor (2) the current velocity is dependent; (1) on the angle, increasing with the deviation of the wave orthogonals from a direction normal to the beach; (2) on the height of the breakers, increasing with the height; (3) on the wave period, decreasing with increase in wave period; and (4) on the slope of the foreshore, increasing with the slope. The present study has demonstrated that other factors must be considered.

On some occasions currents were seen to be moving actively against the direction of approaching waves. The best examples of these counter-posed currents were found in the vicinity of submarine canyons (7). The explanation of these counterposed currents was not difficult to find. It was observed that the currents were moving away from the area of the largest breakers, which was the zone of convergence on one side of a submarine canyon (3). This is illustrated in Figure 7. It was concluded that the water was piled up at the convergence due to shoreward migration and that this developed a gradient on either side with resultant currents. The currents after moving away from the convergence were deflected seaward in the form of rip currents. In one case the currents outside the breakers were measured and found to be converging toward the point of high breakers and thence moving shoreward. In this way large eddies are set up. The longhsore currents could be called the feeder currents of rips (5) although they are essentially longshore currents and have continuity of many hundreds of feet along the shore. Actually, most longshore currents can be shown to be related to rips because invariably they can be traced to a locality where the current turns seaward into a rip.

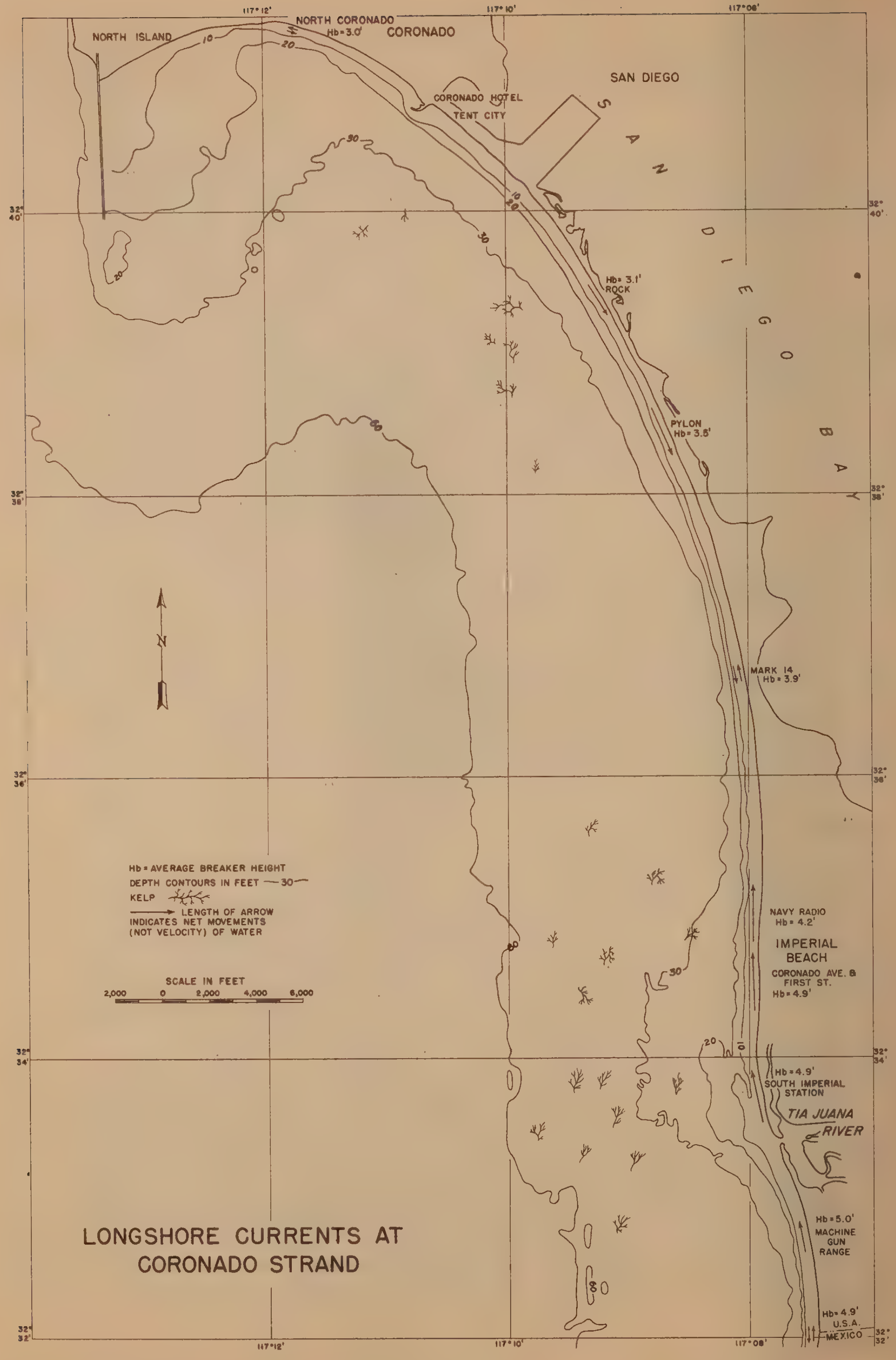
On certain days long, even-crested waves were seen approaching the coast with angles of incidence of the orthogonals far too small to produce appreciable currents. However, measurements in the surf zone showed currents up to about 2 knots. The currents in these cases were observed in areas where the shore is practically straight and where the submarine topography, so far as could be determined from detailed soundings, has no appreciable relief. However, there appeared to be some convergences possibly related to patches of kelp or to minor topographic irregularities not shown on the chart. The currents appear to move away from the convergences and move seaward in between convergences in the form of rips so that the explanation is essentially similar to that for the counterposed currents discussed above.

On two days, during one of which the writer took part in the work, a survey between Torrey Pines Station and North Oceanside was made under conditions where the waves appeared to be approaching normal to the coast, but instead of finding currents approaching rips equally from the two directions, the currents were dominantly to the south; 11 south to 3 north in one case, and 10 south to 3 north in the other. On each day, one of the north currents was related to an approach of waves from the south, but no north approach could be ascertained for the southerly currents. It is possible that the currents were related to a small angle approach from the north which could not be detected. However, the currents had velocities up to almost one knot, much too strong to be entirely the result of any small angle of approach. It seems probable that a general flow along the coast, perhaps a reflection of offshore circulation, was the cause of this general direction although the eddies associated with rip currents were probably responsible for the high velocities. In this connection it should be pointed out that the currents were not counted as to direction where there was a rip current in the immediate vicinity of the station.

Another cause of longshore currents must be wind stress on the water surface. Unfortunately, little opportunity was offered for testing the effectiveness of this cause. The prevailing current outside the breakers may influence the longshore currents. These outer currents have complex causes related to the density of the water masses and the prevailing winds.

Coronado Strand

General description. - One of the longest beaches in California extends north from the Mexican border for 14 miles to the breakwater at the entrance of San Diego Harbor. (See Figure 2) It is broken only at the mouth of the Tia Juana River, a mile and a half north of the Mexican boundary. The opening at this point is maintained by strong tidal currents. The coast is all low except at the very southern end where there are bluffs inside a narrow beach. The shore has been essentially in the same place throughout history, although the building of the breakwater at the entrance to San Diego Harbor (1893-1904) caused cutting which moved eastward from the center of North Island to the Coronado Hotel as the breakwater was lengthened. The cut was stopped by the building of sea walls along the front of Coronado Island. Fill took place next to the breakwater west of the retrograded shore line. Another change in shore line south of Tent City was due to the dumping of sand dredged from San Diego Bay on the foreshore (1939-1945). Since that time the shore line has been rapidly returning to its earlier position.


117° 12'
117° 10'
117° 08'
NORTH CORONADO
Hb = 3.0'
CORONADO
NORTH ISLAND
SAN DIEGO
CORONADO HOTEL
TENT CITY
SAN DIEGO BAY
10
20
30
60
80
Hb = 3.1'
ROCK
PYLON
Hb = 3.5'
MARK 14
Hb = 3.9'
NAVY RADIO
Hb = 4.2'
IMPERIAL BEACH
CORONADO AVE. & FIRST ST.
Hb = 4.9'
Hb = 4.9'
SOUTH IMPERIAL STATION
TIA JUANA RIVER
Hb = 5.0'
MACHINE GUN RANGE
Hb = 4.9'
U.S.A.
MEXICO
32° 40'
32° 38'
32° 36'
32° 34'
32° 32'
N
Hb = AVERAGE BREAKER HEIGHT
DEPTH CONTOURS IN FEET —30—
KELP
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER
SCALE IN FEET
2,000
0
2,000
4,000
6,000

LONGSHORE CURRENTS AT CORONADO STRAND

FIGURE 2

In the vicinity of Tia Juana River, there is a broad alluvial plain inside the beach. Two miles to the north of the river the plain is replaced by a narrow strand which separates San Diego Bay from the open ocean. This low spit extends for 6 miles to a point where it is replaced by the two broad hilly tracts of Coronado and North "Island", both of which are actually former islands tied to the land by a narrow beach or tombolo.

South of Coronado City the beach runs nearly north and south and is gently concave seaward except for a slight convexity just north of the Tia Juana River. The concavity becomes more pronounced at Coronado and the direction of the shore line changes to east and west, even swinging a little south of west at the breakwater.

The submarine relief along the shore shows a notable bulge of the 30-foot contour just north of the Tia Juana River. The bulge is less pronounced in the 10- and 20-foot contours at the same place. North of the tombolo the contours bend out from the shore leaving a broad shallow zone in the area near the breakwater. Elsewhere the contours are fairly uniform and the slope to the 30-foot contour is about 2 per cent.

The breaker heights are almost always greater at the south end of Coronado Strand and show a continuous decrease as far north as the observations were carried. The yearly average varies from 5 feet to the south to 3 feet to the north. The decrease is due largely to the protection provided by the breakwater and Point Loma. A slight protection to the south might be afforded by the Coronados Islands which lie 12 miles in a southwesterly direction.

Analyses of the beach sands obtained along the Strand in 1939 were provided the writer by Dr. U. S. Grant. According to these analyses the sands are coarsest at the south end of the beach as might be expected since the only appreciable source of sand is from the south. In general the medians show a decrease to the north although some coarsening occurs from Tent City to the eastern end of North Island. Farther west the medians decrease steadily as far as the breakwater. According to Grant the sand varied from 130 to 420 microns along the Strand, although the coarsest sand is actually in the slough of the Tia Juana River. The coarsest beach sand, which is at the Mexican Boundary, is 360 microns.

Current system. – The currents observed at the nine stations on the Coronado Strand are indicated in table 1.

TABLE 1
Coronado Strand Currents

Station	Height of breakers	No. of days observed			Average velocity in knots		Number times velocity		
		N	S	Neut.	N	S	N	S	Net
Mexican Border	4.9	10	10	10	0.70	0.54	7.0	5.4	N
Machine Gun Range	5.0	15	8	9	.68	.70	10.1	5.6	N
South Imperial (Tia Juana R. delta)	4.9	17	9	4	.76	.55	12.9	4.9	N
Coronado Avenue & First Street	4.9	16	9	11	.75	.51	12.0	4.6	N
Navy Radio	4.2	19	2	13	.60	.50	11.4	1.0	N
Mark 14	3.9	11	15	10	.56	.55	6.2	8.3	S
Pylon	3.5	7	22	6	.41	.58	2.8	12.8	S
Rock	3.1	10	15	11	.31	.77	3.1	11.5	S
North Coronado	3.0	16	10	8	.49	.68	7.8	6.8	N

Examination of the current data shows that there is a definite north drift along the southern portion of the beach while the trend is to the south in the northern portion. The currents are almost balanced at an intermediate point and at the northernmost station. Examination of the submarine topography in relation to this change in trend does not prove particularly helpful. The bulging contours just north of the Tia Juana River might be expected to produce a convergence in this area so that currents might flow in opposite directions on the two sides but the observations show that they flow principally to the north on both sides of this bulge. However, the decrease in north current to the south of the bulge may indicate a relation to the contours. One factor influencing the longshore current system is the changing trend of the coast. To the north of the area of balanced currents the coast trends much more to the northwest, therefore waves approaching from the west will tend to develop a southerly component in this area. The balancing of this flow at North Coronado is explained by the greater influence of the nearby breakwater which makes the westerly and northwesterly approaching waves ineffective. The northerly currents to the south may be partly the result of a north flowing counter current outside the breakers which is developed in the lee of Point Loma. The temperature observations along the Strand show an accordance with the converging currents. The temperatures are for the most part higher off the central portion of this beach indicating that the water has been flowing along the coast in the shallow area where insulation is greater.

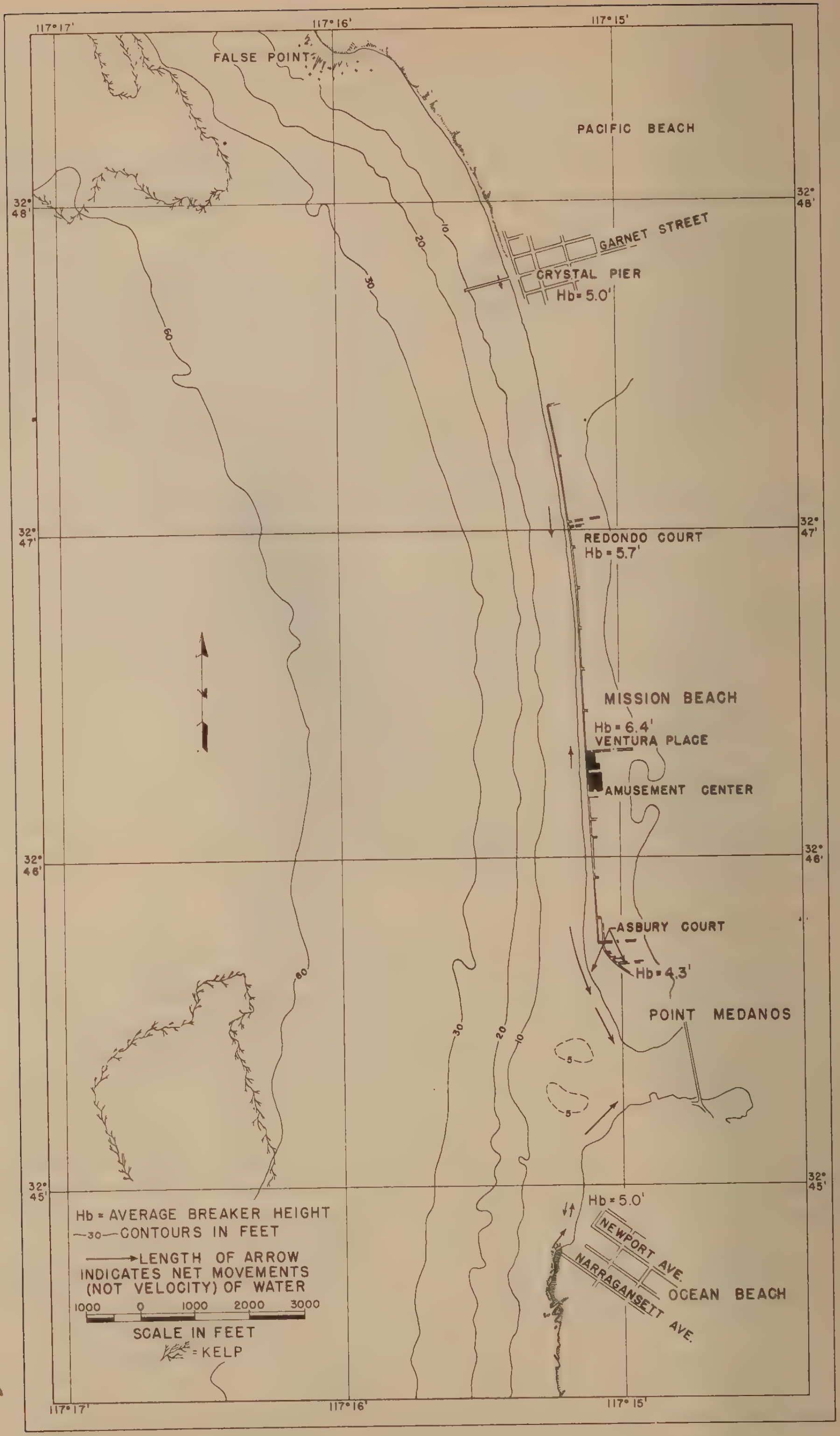
One effect of the circulation is that the Strand is evidently supplied with its sand from both ends. The supply from the south is easily explained since the Tia Juana River empties into this area during floods. The northern source is not as evident. Possibly sand is carried north along the sea floor outside the surf zone and then returns south along the shore. This type of circulation would account for the fill on the east side of the San Diego Harbor breakwater and on the northwest side of the Coronado Hotel jetty. The beaches south of the Tia Juana River may be supplied from erosion of the cliffs which extend south of the international boundary.

The presence of an extensive cobble and boulder mass in the area of the Tia Juana River and two miles north may be accounted for by the pronounced north drift observed in the vicinity of the river mouth. This would carry the sand and silt beyond the cobble and boulder area, depositing the sediment to the north.

Seasonally, the currents showed some changes in net movement. In the fall and summer the movements for the Strand as a whole were predominantly north, whereas they were predominantly south in the winter and spring. This agrees in general with the directions of wave approach at these seasons.

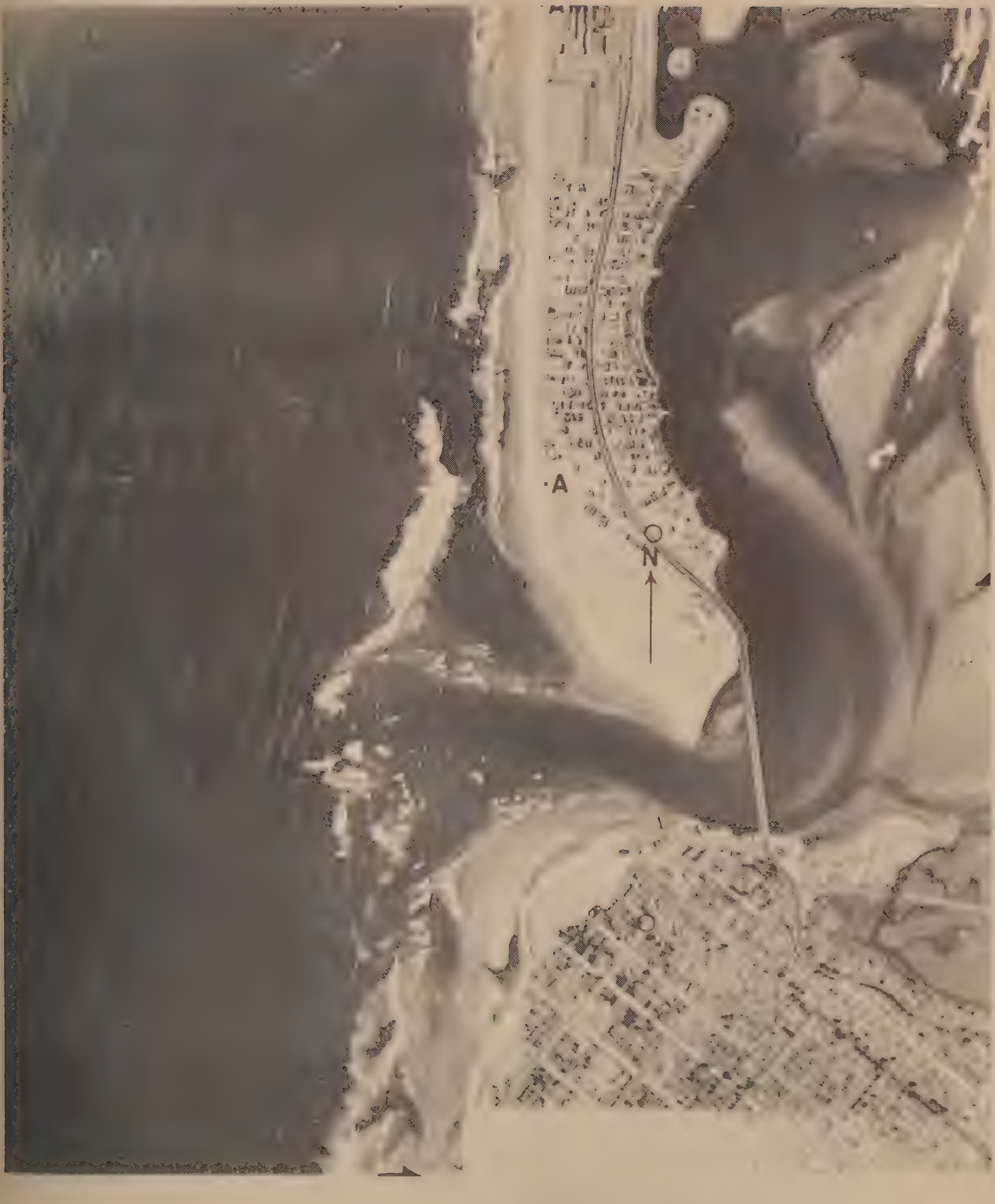
Mission Beach

General description. - Mission Beach is a spit built most of the way across the mouth of Mission Bay. (See Figure 3). In this area there are five stations although observations were made at only two stations during the last six months of the survey. The northern station is at Crystal Pier, somewhat north of the spit and lying off the low terrace which forms Pacific Beach. The second station is off the northern part of the spit a mile south of Crystal Pier. The third station is in the vicinity of the Amusement Center in the center of the spit while the fourth station is near the southern end of the spit and slightly protected by the northern end of a bar off the entrance to Mission Bay, (Figure 4). The southern station is at Ocean Beach south of the bay entrance and near the beginning of the rocky coast which forms the west side of Point Loma. Aside from the station near the entrance to Mission Bay all of the areas are almost completely unprotected from the open sea. The submerged portion of the beach slopes seaward at about one per cent to a depth of 30 feet, except near the entrance to the bay where the bar intervenes. Sources of sand


117°17'
117°16'
117°15'
FALSE POINT
PACIFIC BEACH
32° 48'
GARNET STREET
CRYSTAL PIER
Hb = 5.0'
10
20
30
60
32° 47'
REDONDO COURT
Hb = 5.7'
MISSION BEACH
Hb = 6.4'
VENTURA PLACE
AMUSEMENT CENTER
32° 46'
ASBURY COURT
Hb = 4.3'
POINT MEDANOS
5
32° 45'
Hb = 5.0'
NEWPORT AVE.
NARRAGANSETT AVE.
OCEAN BEACH
Hb = AVERAGE BREAKER HEIGHT
—30— CONTOURS IN FEET
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER
1000 0 1000 2000 3000
SCALE IN FEET
= KELP

LONGSHORE CURRENTS AT MISSION BEACH AND ENTRANCE TO MISSION BAY

FIGURE 3



AERIAL PHOTOGRAPH OF THE ENTRANCE TO MISSION BAY. NOTE THE SUMERGED BAR AND WAVE REFRACTION. THE CURRENTS AT A. (ASBURY COURT) ARE ALMOST ALWAYS SOUTHERLY BECAUSE OF THE BENDING OF THE WAVE CRESTS. NOTE THE CHANNEL THROUGH THE CENTER OF THE BAR WHICH TAKES CARE OF THE OUTFLOW OF THE TIDE.

FIGURE 4

are provided by the erosion of the alluvial cliffs north of the spit and rarely by the flow of sediment out of Mission Bay during floods. The dams in the back country largely prevent such outflow at present.

Old maps of Mission Beach show that the spit has been growing steadily to the south. In 50 years it has advanced about 500 feet. The old chart shows that there was a bar off the enlarged entrance to the bay in 1895 similar to the present bar.

The sand on the beaches at the entrance to Mission Bay was analyzed by the U. S. Engineers (1) and was found to be close to 250 microns in diameter so that it is on the line between fine and medium sand. The coarsest sand was found near the entrance to the bay on either side. The minimum occurs near the north end of the spit with slight increases farther north. South of the south entrance the medians show a decrease.

The breakers are somewhat higher off the center of the Mission Beach spit and are decidedly lower in the shelter of the bar although they are fully as high on the outside of the bar. The breakers are usually higher at the Amusement Center than at Redondo Court and Crystal Pier to the north, but the difference is not great.

Current system. - Current observations are available from four sources. The periodic observations throughout the year provide the largest body of data, but numerous measurements have been made at Crystal Pier including 6 months of observations from October 1947 to April 1948 taken at an average interval of two days and scattered observations in connection with pier profile measurements. The U.S. Engineer (1) took repeated measurements of the currents in September and October 1940 near the entrance to the bay on both sides and a little less than one mile north and south of the entrance. Recently the currents were observed by Captain W. H. Quinn at closely spaced stations along the southern end of Mission Beach north of a jetty which was under construction. All of these data will be used in drawing conclusions. The average longshore current conditions in the Mission Beach area are shown in Table 2.

The most striking feature of the currents before the jetty construction is that near the bay entrance the predominant flow along shore is towards the entrance. Although these currents are strongest during flood tides and are sometimes reversed during ebb tides, in general they flow towards the entrance even while the tide is running out of the bay. The explanation appears to lie in the bending of the waves around both ends of the crescent bar which directs the flow toward the entrance on either side (Figure 4). It is also possible that high waves north and south of the bar may pile up the sea level developing a gradient which drives the water towards the entrance. The currents moving towards the entrance during ebb tide must, of course, be balanced by a stronger outflow in the center.

TABLE 2
Mission Beach Area Currents

Station	Height of breakers	No. of days observed			Average velocity in knots		Number times velocity		
		N	S	Neut.	N	S	N	S	Net
*Narragansett Ave (Sep., Oct. only)		76%	24%						N
Newport Ave. (Ocean Beach)	5.0	14	5	9	0.56	0.60	7.9	4.2	N
*South Entrance to Mission Bay (Sep., Oct. only)		100%	0						N
*North Entrance		15%	85%						S
Asbury Court	4.3	5	21	4	.67	.94	2.5	20.0	S
Amusement Center (Jan.,Jul only)	6.4	11	6	6	.49	.50	5.4	3.0	N
*Ventura Place (Sep., Oct. only)		60%	40%						N
Redondo Court	5.7	5	12	5	.67	.64	3.3	7.6	S
Crystal Pier	5.0	55	54	15	.55	.50	30.0	27.0	N

* Stations have data from U. S. Engineers

The currents evidently converge north of the Amusement Center. The resulting outflow may account for the particularly bad rip currents in this vicinity which are a cause of much concern to the lifeguards. The speed and direction of longshore currents here as in many other places are greatly dependent on the nearness to the seaward moving rips.

As a result of jetty construction a rip current has developed north of the jetty. This was observed during current surveys on four occasions in July 1949. These closely spaced observations also showed alternating north and south currents which indicated the existence of a series of eddies along the shore. Observations outside the breakers gave partial confirmation for these circulation cells.

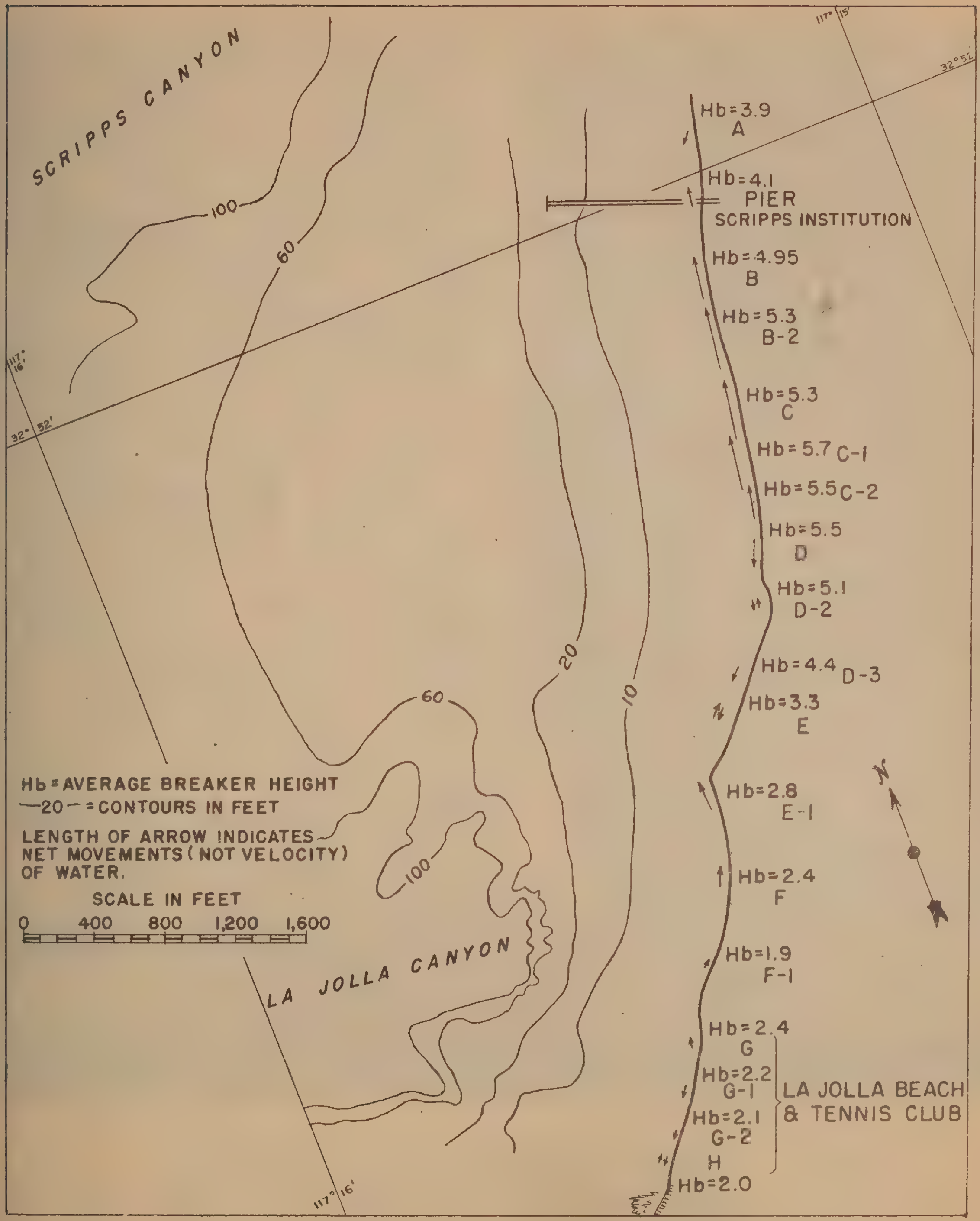
Scripps Beach, La Jolla

General description. - The long beach extending for over a mile from the Scripps Institution to the La Jolla Beach and Tennis Club is referred to here as Scripps Beach (Figures 5 and 6) although it is known locally as Long Beach. The longshore current system adjacent to this beach is of particular interest since the existence of pronounced submarine canyons causes a convergence and divergence of the wave orthogonals, as has been explained previously (3). The beach in general is gently concave. It has two small projecting points, one on either side of La Jolla submarine canyon head, the northern one being the larger of the two. A third, smaller point exists just south of the pier. A considerable concavity exists at about the middle of the beach and a more gentle concavity at the head of the submarine canyon. The sea floor contours along the shore bend out around each of the points. To the north the beach terminates at a rocky point 500 feet north of Scripps Institution pier (Figure 5). To the south the beach terminates at another rocky point just south of the southern boundary of the beach and Tennis Club. It is notable that both of these rocky points are found a short distance south of two submarine caynon heads (La Jolla and Scripps Canyons).

The wave crests bend in toward the shore at the canyon head, particularly during long-period waves. Conversely they bend away from the shore producing a slight convergence outside each of the beach convexities (Figure 5). Inside the canyon the breakers are greatly reduced, averaging only 1/3 as high (at F-1) as the breakers to the north (at D). It is notable that the breakers at the convexities north and south of the canyon are much smaller than in the zone about half way between the two canyons (C to D).

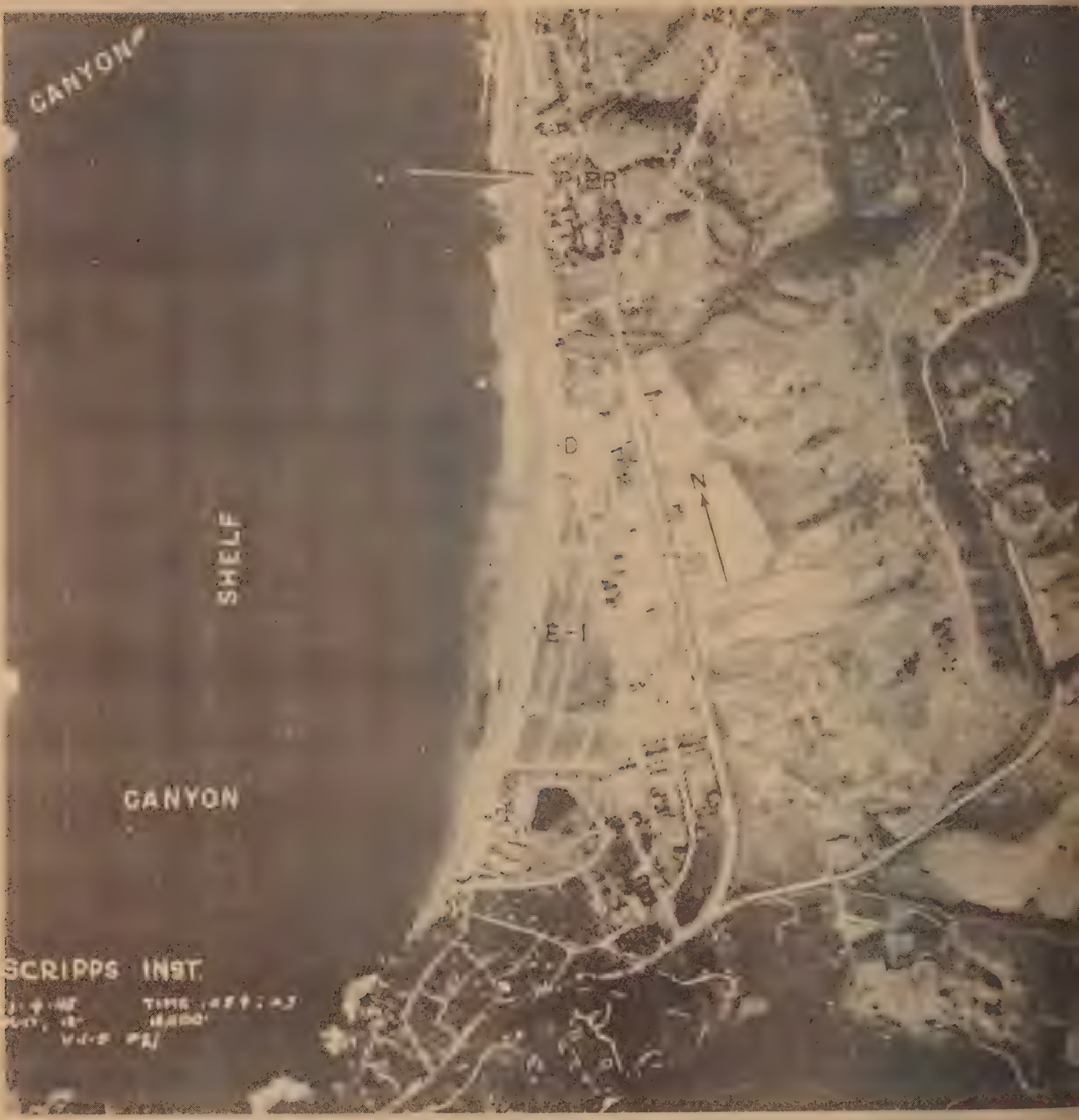
According to analyses by Commander Panzarini, the sand on Scripps Beach has an average median diameter of 183 microns. Coarser sand with a median of 246 microns is found at station A near the rocky point. The finest sand with a median of 167 microns is found near the north side of the canyon head. The mica content of the sand varies considerably, being very high in the season of small waves, especially at the south end of the beach near the canyon.

Current system. - By far the most complete set of observations on the currents is available from Scripps Beach. During the year of current studies 18 regular stations averaging 300 feet apart were observed in the positions indicated in Figure 5. In addition 240 observations of current directions have been made both inside and outside of the breakers at the Scripps Institution pier, and over 100 observations were obtained from noting the trend of life lines at the Beach Club just south of La Jolla submarine canyon. A considerable number of miscellaneous observations during the past years have provided general information concerning the currents at Scripps pier. Special observations with triplanes and a weighted


SCRIPPS CANYON
117° 15'
32° 52'
Hb=3.9
A
Hb=4.1
PIER
SCRIPPS INSTITUTION
Hb=4.95
B
Hb=5.3
B-2
Hb=5.3
C
Hb=5.7 C-1
Hb=5.5 C-2
Hb=5.5
D
Hb=5.1
D-2
Hb=4.4 D-3
Hb=3.3
E
Hb=2.8
E-1
Hb=2.4
F
Hb=1.9
F-1
Hb=2.4
G
Hb=2.2
G-1
Hb=2.1
G-2
H
Hb=2.0
LA JOLLA BEACH & TENNIS CLUB
100
60
20
10
117° 16'
32° 52'
N
Hb = AVERAGE BREAKER HEIGHT
—20— = CONTOURS IN FEET
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER.
SCALE IN FEET
0 400 800 1,200 1,600
LA JOLLA CANYON
117° 16'

LONGSHORE CURRENTS AT SCRIPPS BEACH

FIGURE 5


CANYON
PIER
D
N
SHELF
E-1
CANYON
SCRIPPS INST.

AERIAL PHOTOGRAPH OF SCRIPPS BEACH AT LA JOLLA. NOTE THE NARROW SURF ZONE AT THE CANYON HEAD, F TO C, THE WIDE SURF ZONE AT THE CONVERGENCE, C TO E, AND THE RIP CURRENTS ON BOTH SIDES OF THE CONVERGENCE AT B AND E. ANOTHER RIP MAY BE SEEN JUST NORTH OF F.

FIGURE 6

ball which rolls along the bottom have also been made. Furthermore, the rip currents of the area have been observed for the past 10 years and were given special study in 1940 (5). As a result the opportunity to draw conclusions from this area is unique, although the presence of the submarine canyons does not necessarily make these conclusions valid for most other areas.

TABLE 3

Scripps Beach, La Jolla, Currents

Station	Height of breakers	No. of days observed			Average velocity in knots		Number times velocity		Net
		N	S	Neut.	N	S	N	S	
H	2.0	15	12	14	0.29	0.45	4.36	5.38	S
G-2	2.1	19	23	8	.28	.34	5.34	8.72	S
G-1	2.2	47	66	12	.27	.32	12.69	21.10	S
G	2.4	17	14	6	.40	.40	6.85	4.40	N
F-1	1.9	16	9	13	.32	.28	5.06	2.52	N
F	2.4	26	7	3	.37	.44	9.66	3.06	N
E-1	2.8	26	6	6	.45	.59	11.68	3.55	N
E	3.3	19	15	3	.59	.57	11.17	8.60	N
D-3	4.4	19	11	3	.55	.79	10.45	8.63	N
D-2	5.1	15	6	9	.45	.57	6.83	3.40	N
D	5.5	13	17	10	.38	.43	4.90	7.37	S
C-2	5.54	14	15	5	.55	.40	7.82	5.97	N
C-1	5.7	16	8	6	.65	.37	10.4	2.96	N
C	5.3	19	9	4	.55	.39	10.45	3.47	N
B-2	5.3	15	10	6	.55	.35	8.30	3.50	N
B	4.95	46	28	22	.50	.31	23.00	8.70	N
Scripps pier	4.1	182	90	35	.45	.49	82.00	44.00	N
A	3.9	10	14	7	.26	.32	2.6	4.48	S

Table 3 shows the average current conditions. A definite pattern can be observed from these currents. The three stations, (H, G-2, G-1) located somewhat south of the canyon have a slight dominance of south currents whereas G and F-1 at the head of the canyon and F and E-1 just to the north have north currents. The next three stations (E, D-3, D-2) have more north currents than south currents but the transport of sand is probably greater to the south because during the periods of large waves, when transport is enormous, the currents are mostly to the south. Farther north, six stations have north currents and the sand transport must be in the same direction. The northernmost station (A) has a slight south current.

The explanation of the current pattern depicted in Figure 5, depends in part on the wave fronts which are retarded on either side of the canyon. This bend in the wave front tends to drive currents away from the canyon head. To the north of the canyon a piling up of the water in the zone of highest breakers (C to D) results in the flow along the shore away from this convergence. This factor appears to have produced the strongest currents in this area. The average south current at D-3 of 0.79 knots is the best illustration and is found in a zone where wave heights show great variation in a short distance. This same flow away from a zone of high waves is also observed in the case of the convergence north of Scripps Canyon. The cause of these strong flows is apparently the piling up of the water at the convergence. Some of the water flows more or less directly outward as rips in the convergence, but much of it moves along the shore. It is perhaps a coincidence that the currents are diverging away from the area where there are exposed cliffs of alluvium (Figure 6, vicinity of C). These cliffs are being eroded almost a foot a year by the waves (6). The area to the south of the cliffs is not being eroded because of the sea walls, but the history of the area indicates that it was a zone where deposition took place before man-made structures existed. In fact the southern portion was once a bay; subsequently, a bar was built across this bay and the lagoon was filled partly by man.

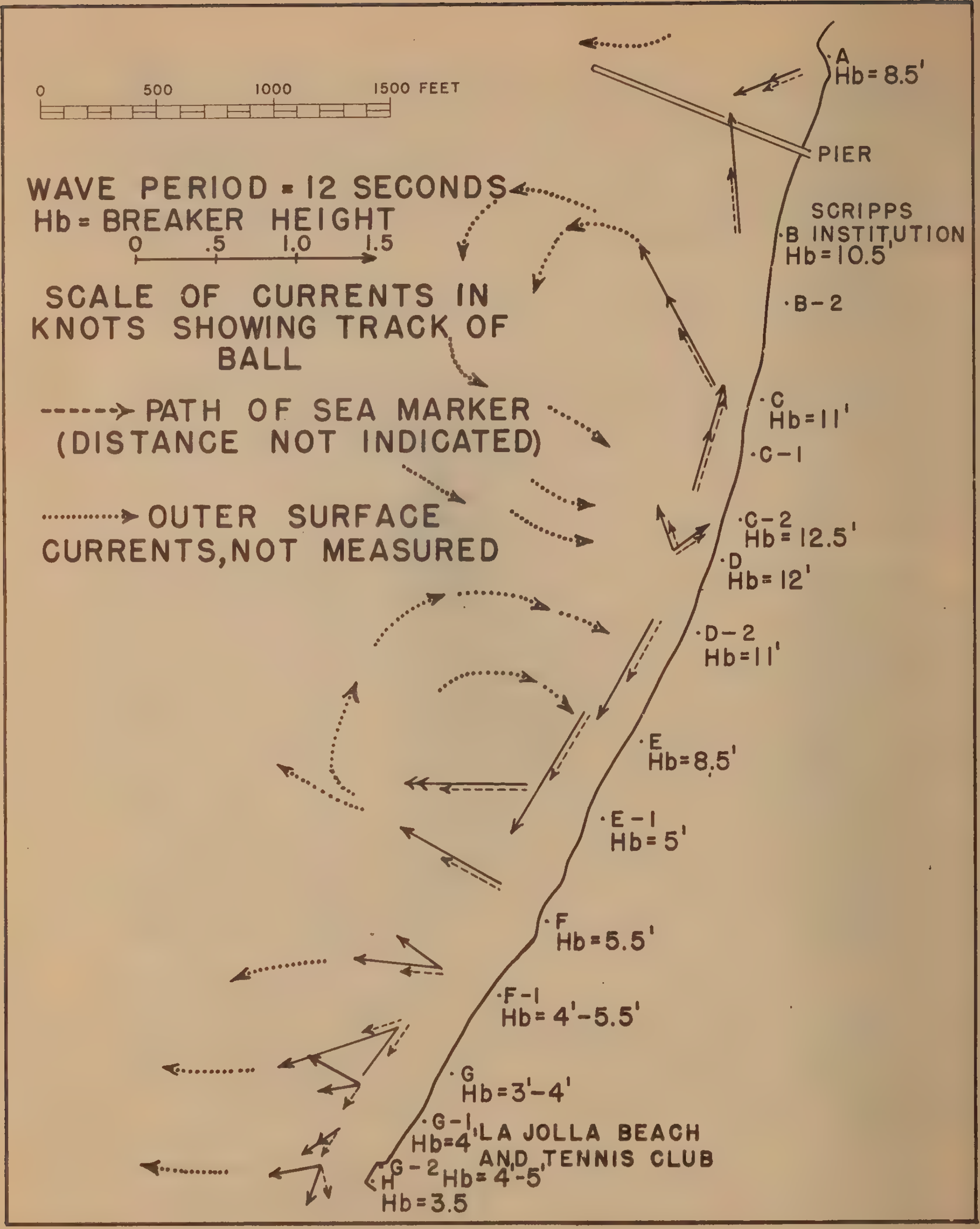
An examination of Figure 5 suggests the explanation for the absence of sand along the shore in the area south of the Beach Club.. Since the source of the sand appears to be largely the cliffs along the northern half of the beach, southerly currents would appear to be necessary in order to transport the sand to the south of the canyon. However, the southerly currents give out at about station E and the prevailing currents flow north away from the canyon at both E-1 and F. It is only on rare occasions that the flow at these two stations has been reversed.

The nature of the offshore currents in this area has been investigated to some extent. The current observations made along the length of the Scripps Institution pier show that flow is not uncommonly in opposite directions inside and outside the breakers. The same is also observed elsewhere along the shore. It seems likely that we are dealing with a series of eddie such as are indicated in Figure 7. On one occasion such an eddy was clearly demonstrated by the path of a buoy attached to a submerged triplane. The triplane moved in rapidly through the breakers and flowed swiftly along the shore to the north and then diagonally out to the southwest. Outside the breakers it completed its circuit with a slower movement to the north. A more complete description of these currents is given elsewhere (7).

The projecting point of sand found on the north side of the canyon head and reflected in the submarine contours along the shore appears to be related to the converging current systems at these positions. If the beach were straightened here, the outbending currents would presumably leave an area of slack water and eddies inside the point of juncture. In this area deposition would take place and thus the point would be reestablished. The occurrence of the finest sand on this point supports this line of reasoning. A less prominent point is also found near the south end of the canyon. Its cause is not as evident from the observed currents.

It should be emphasized that the currents considered above are average for the Scripps Beach area. A considerable variation exists from time to time. Currents resulting from a strong northwest blow have been observed on two occasions. In both cases the longshore currents were very strong to the south along the entire beach from the pier to the Beach Club with little regard to the canyon. Since the waves had short periods, about 8 seconds, the canyon had little effect. Short period waves "feel" bottom in much shoaler depth than long-period waves of the same height. However, the transport of sand to the south which resulted from these currents would not have been felt beyond the Beach Club since strong rip currents developed in this area, carrying the sediment seaward for thousands of feet. Various eddies were observed off the southern end of the Beach Club. With a blow from the southwest and high breakers the currents were not as consistent although more north currents were observed than usual. In one case when the waves were very small and of short period, D. L. Inman found that the currents diverged on either side of the two beach points and flowed away from the points. Numerous other patterns have been detected, apparently varying according to wave period, direction of wave approach, and direction of wind. The eddies and rip currents which are found associated with these different conditions are the subject of another report (7).

Seasonally the currents at Scripps Beach showed, a maximum of north currents in early winter when about 80 per cent of the currents were to the north, and a maximum of south currents in early summer when the north and south currents were about balanced. This differs from the situation at Coronado and Mission Beaches where the time of most north currents was in the fall. The largest number of neutral currents at Scripps Beach was in the early winter.


0
500
1000
1500 FEET
WAVE PERIOD = 12 SECONDS
Hb = BREAKER HEIGHT
0
.5
1.0
1.5
SCALE OF CURRENTS IN KNOTS SHOWING TRACK OF BALL
-----> PATH OF SEA MARKER (DISTANCE NOT INDICATED)
··········> OUTER SURFACE CURRENTS, NOT MEASURED
A
Hb = 8.5'
PIER
SCRIPPS INSTITUTION
B
Hb = 10.5'
B-2
C
Hb = 11'
C-1
C-2
Hb = 12.5'
D
Hb = 12'
D-2
Hb = 11'
E
Hb = 8.5'
E-1
Hb = 5'
F
Hb = 5.5'
F-1
Hb = 4'-5.5'
G
Hb = 3'-4'
G-1
Hb = 4'
LA JOLLA BEACH AND TENNIS CLUB
G-2
Hb = 4'-5'
H
Hb = 3.5

LONGSHORE CURRENTS AT
SCRIPPS BEACH, 14 MAY 1948

FIGURE 7

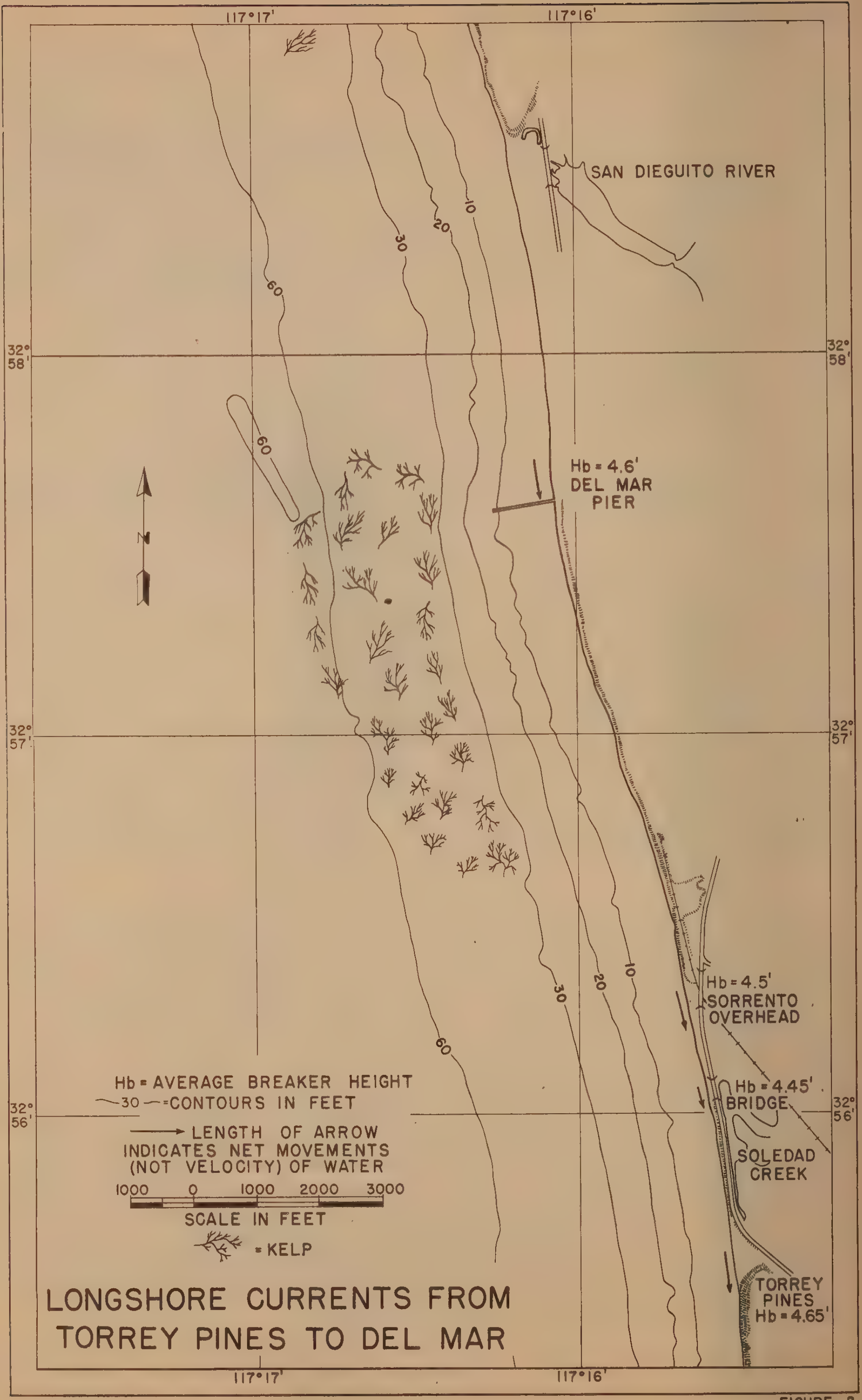
Torrey Pines to North Oceanside

North of Scripps Institution the coast runs straight for 40 miles. Almost the entire length is bordered by beaches, although very small rocky points are found in a few places. In this distance the trend of the coast changes gradually from almost north at the south end to north 40° west at the north end. A series of 16 stations was observed in this area, most of them being along the beaches at the mouths of the larger valleys. Such beaches are bars built across the old estuaries, like the south end of Scripps Beach. Since no easy access to beaches was found north of Oceanside, there is a section of this straight part of the coast with a length of 15 miles which lacks stations. The current conditions in the entire area are shown in Table 4.

Torrey Pines State Beach (Sorrento Valley)

Three stations were located along the bar which cuts off Sorrento Valley from the sea (Figure 8). The southernmost of these (Torrey Pines) is located just north of the bluffs of Torrey Pines Park. The middle station (Soledad Bridge) is opposite the blocked end of the estuary and the northern station (Sorrento Overhead) is near the bluff north of the valley mouth. The inshore contours run essentially parallel to the coast past all of these stations but there is a significant outbend of the 300-foot contour just north of Sorrento Overhead (Figure 1). Although the breaker height averages are all approximately the same, $4\frac{1}{2}$ feet, it has been observed that under conditions of large breakers approaching normal to the coast some convergence takes place north of Sorrento, possibly the result of the small outbend of the 300-foot contour off this place (Figure 1). The sand has a median grain size of about 200 microns, coarsening slightly to the north. During the summer of 1949, measurements were made by Captain W. H. Quinn at 12 stations along this beach on 12 occasions. Currents were measured outside the breakers during two of these runs.

The longshore currents in this area are dominantly south in contrast to Scripps Beach. After the year's observations were over, a return to this stretch of beach under storm and large swell conditions showed the following: A strong northwest wind with short period waves was accompanied by strong southerly currents at all three stations. The transport to the south under these conditions must have been tremendous, probably exceeding in one day all of the transport throughout a year of ordinary conditions. During a period of large 15-second swells approaching normal to the shore without wind, large currents were observed at the north and south ends of the beach converging on the center where there was a powerful rip current moving seaward. The strong southerly current at Soledad Bridge Station appeared to have some relationship to the flow away from an area to the north where very large breakers were seen. On one occasion the currents were flowing north outside the breakers and dominantly south inside. This was during a period when a southerly wave approach was observed from the cliffs.



LONGSHORE CURRENTS FROM TORREY PINES TO DEL MAR

117°17'
117°16'
32° 58'
32° 57'
32° 56'
SAN DIEGUITO RIVER
10
20
30
60
N
Hb = 4.6'
DEL MAR PIER
Hb = 4.5'
SORRENTO OVERHEAD
Hb = 4.45'
BRIDGE
SOLEDAD CREEK
TORREY PINES
Hb = 4.65'
Hb = AVERAGE BREAKER HEIGHT
30 = CONTOURS IN FEET
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER
1000 0 1000 2000 3000
SCALE IN FEET
= KELP

FIGURE 8

TABLE 4

Torrey Pines to Oceanside Currents

Station	Height of breakers	No. of days observed N	S	Neut.	Average velocity in knots N	S	Number times velocity N	S	Net
Torrey	4.6	10	11	12	0.32	0.66	3.2	7.3	S
Soledad Creek	4.4	6	19	11	.57	.45	3.4	8.5	S
Sorrento Overhead	4.5	5	15	12	.48	.50	2.4	7.55	S
Del Mar Fence	4.6	7	13	8	.39	.57	2.7	7.4	S
Solana Beach	4.4	3	12	7	.25	.55	..75	6.7	S
Seaside Camp	4.1	8	11	10	.50	.59	4.0	6.0	S
Beacon Inn	4.1	10	15	8	.38	.55	3.8	8.3	S
Moonlight Beach	4.4	6	12	7	.55	.59	3.3	7.1	S
San Marcos Creek	4.4	8	16	9	.32	.50	2.6	8.8	S
Encinas Creek	4.1	8	20	4	.34	.45	2.7	9.0	S
Aqua Hedionda	3.8	9	18	4	.36	.76	3.3	13.7	S
Buena Vista Cr.	3.9	9	19	4	.31	.57	2.8	12.1	S
Loma Alta Cr.	3.9	9	20	3	.43	.54	3.9	10.8	S
Wisconsin Ave. Oceanside	4.1	9	18	9	.83	.67	7.5	12.0	S
Oceanside Pier	4.2	19	24	16	.78	.77	14.8	18.5	S
N. Oceanside (San Luis Rey Valley)	4.6	9	20	4	.73	.68	6.6	13.6	S

Scattered Stations south of Oceanside. - North of Sorrento Valley a series of nine isolated stations was used, mostly at the mouths of valleys. The first one is near Del Mar Pier (Figure 8), but at a sufficient distance to the north to avoid special pier effects. This station is located off a beach near the north end of the bluffs which extend between Sorrento and San Dieguito Valleys. The breakers average 4.6 feet which is about the same as at Sorrento. The contours show that the bottom is essentially smooth with the same gentle slope as off Sorrento Valley, but the bottom is largely rock for half a mile out beyond the 10-foot contour, with scattered masses of kelp growing up to the surface. The sand of the beach has a median of 220 microns. The currents are dominantly south with a 2 to 1 ratio between south and north currents.

At Solana Beach (Figure 9) a narrow valley comes to the coast between rocky bluffs. The beach runs continuously along the shore but is narrow off the bluffs. The sand has a median diameter of 180 microns. The currents are largely south at Solana with a 4 to 1 ratio numerically and twice the velocity for the south currents.

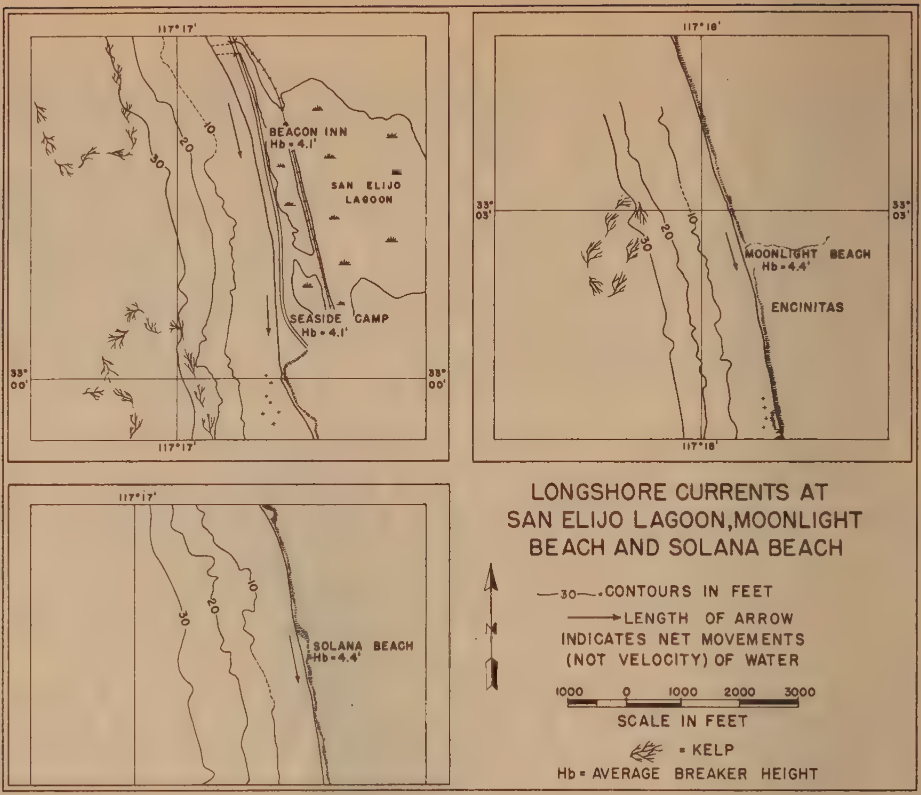
At the bar which cuts off the mouth of San Elijo Lagoon (Figure 9) two stations were measured and for a short time a third. Seaside Camp is near the south end of this beach and is located a short distance north of a rocky point off which submerged shoals cause a decided convergence. The Beacon Inn station is near the center of the beach. The northern station, not maintained because of difficulty of approach, is off the bar at the mouth of the creek. The breakers at San Elijo Lagoon are somewhat smaller, averaging 4.1 feet, probably because of wave convergences to the north and south of the beach. The sand has a median diameter of about 200 microns. The currents at both Seaside Camp and Beacon Inn were dominantly south although the dominance is less pronounced at Seaside Camp than at any other station in this central group. Probably the reason for the greater number of north currents is that the convergence to the south of Seaside Camp tends to throw the current to the north. A few observations by Commander Panzarini at Beacon Inn with a ball, weighted so as to travel on the bottom, indicated that the current at the bottom moved out much more than did the surface current. The observations at the discontinued station at the north end of this beach were made during periods of southerly swell. It was not surprising that a rip current was observed on each occasion, this being the seaward return of the water moving north along the beach.

Moonlight Beach (Figure 9) is located just north of Encinitas. It is a narrow beach at the foot of the small valley of Cottonwood Creek and is terminated by rocky bluffs on either side. The sand has a median diameter of 220 microns. The contours are essentially straight outside the beach although there is a rock patch indicated by the presence of kelp. The currents are dominantly south with a 2 to 1 numerical ratio south to north.

At the mouth of San Marcos and Las Encinas Creeks there are large bars of cobbles with the steep slope usual for coarse material. An apron of sand covers the lower beach. During the summer and fall the sand builds up over the lower portion of the steep front of cobbles and is in turn cut away during the winter. The sea floor is smooth to the south. Rock occurs off San Marcos, but only sand is found off Las Encinas. The breakers are 4.4 feet in height at San Marcos with a decrease to 4.1 feet at Encinas Creek. The sand is similar in size to that of the beaches to the south, having median diameters of 180 and 150 microns, respectively. The currents continue to have a southerly predominance with somewhat of an increase of the south component particularly at San Marcos Creek.

The next two stations to the north were both located on sand bars at the mouths of creeks. At Aqua Hedionda the beach has some cobbles at a high level but is mostly a sand beach, and Buena Vista to the north is all sand. The median sand grain was found to be 224 and 190 microns, respectively. The sea floor continues to have a smooth outward slope. It is mostly sand covered although there is a patch of rock, in 30 feet of water, which terminates northward outside Buena Vista Creek. The breakers are slightly lower averaging a little less than 4 feet. The especially low average breaker height of 3.8 feet at Aqua Hedionda may be due to a slight wave divergence caused by the submarine canyon which heads a mile offshore just to the south. At all of these stations the southerly currents predominate with about twice as many south as north currents observed and with higher southerly velocities particularly at Aqua Hedionda, where the average velocity is twice as great for the southerly currents as for the north. The currents at Aqua Hedionda apparently are not affected by the canyon which lies a mile seaward and terminates at a depth of 250 feet. The small number of neutral currents may also be significant for these stations.

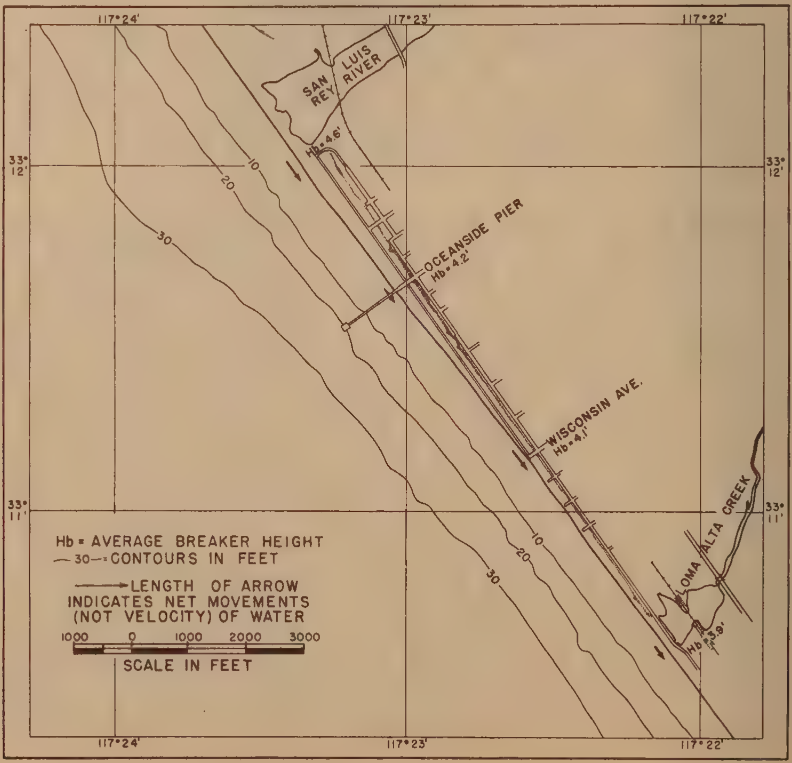
Oceanside area. - Four stations were established on the beach at Oceanside (Figure 10). The southern of these stations is located on the bar at the mouth of Loma Alta Creek. Two of the stations are along the bluffs between the valleys. The north station is located near the termination of the bluffs just south of San Luis Rey Valley. The shore continues straight all along this area. The bottom off Oceanside is apparently all sand covered. The slope to the 20-foot contour continues to be about the same as along all of this straight coast north of La Jolla despite the fact that the median grain size of the beach shows a slight increase being about 270 microns. In general, foreshore slopes vary directly with sand grain diameters. The 30-foot contour is somewhat farther out in the area and bends seaward off the San Luis Rey Valley. Judging from measurements along the pier and from observations at low tide, shallow submerged bars are more common off Oceanside than most of the stations to the south. The submerged bar at Loma Alta was especially persistent. The breaker heights show a progressive increase to the north with the largest (4.6 feet) being recorded at San Luis Rey Valley. The



LONGSHORE CURRENTS AT SAN ELIJO LAGOON, MOONLIGHT BEACH AND SOLANA BEACH

117°17'
BEACON INN
Hb = 4.1'
SAN ELIJO LAGOON
SEASIDE CAMP
Hb = 4.1'
33° 00'
10
20
30
117°18'
33° 03'
MOONLIGHT BEACH
Hb = 4.4'
ENCINITAS
SOLANA BEACH
Hb = 4.4'
N
—30—- CONTOURS IN FEET
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER
1000 0 1000 2000 3000
SCALE IN FEET
= KELP
Hb = AVERAGE BREAKER HEIGHT

FIGURE 9



117°24'
117°23'
117°22'
33° 12'
33° 11'
SAN LUIS REY RIVER
Hb = 4.6'
OCEANSIDE PIER
Hb = 4.2'
WISCONSIN AVE.
Hb = 4.1'
LOMA ALTA CREEK
Hb = 3.9'
10
20
30
Hb = AVERAGE BREAKER HEIGHT
—30— = CONTOURS IN FEET
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER
1000 0 1000 2000 3000
SCALE IN FEET

LONGSHORE CURRENTS IN OCEANSIDE AREA

FIGURE 10

size at this point may be related to the small ridge, shown by the 30-foot contour, which must cause some convergence.

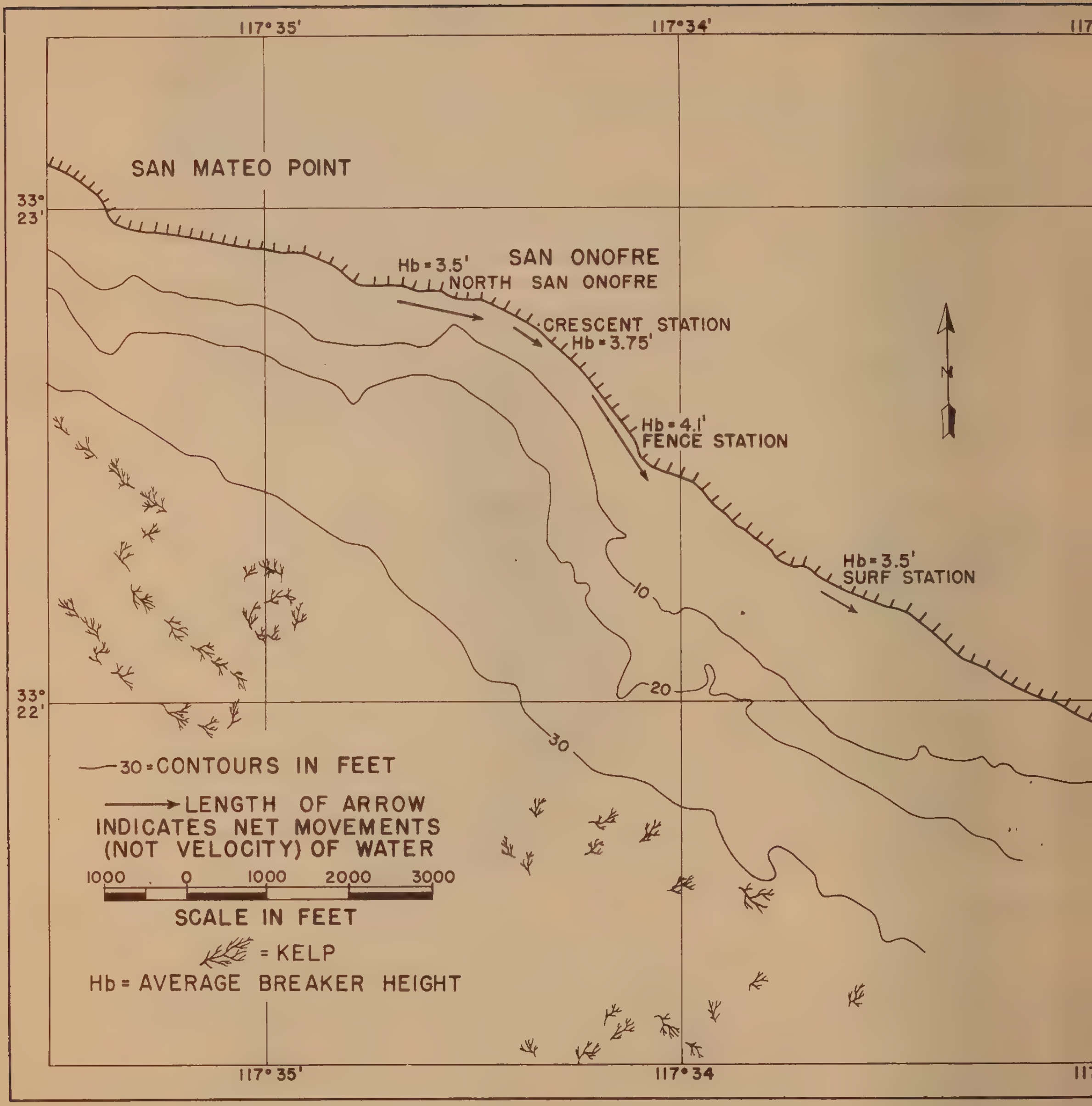
The currents in the Oceanside area are notable for two things; they show greater average velocities than others in southern California with the exception of Loma Alta Creek, and the north flowing currents have an average velocity as great as south flowing currents which is in contrast to all of the stations to the south as far as Beacon Inn. However, approximately the same ratio between number of south and north flowing currents was found as farther south. There may be some significance that neutral currents are much higher at both of the stations at the foot of the bluffs than at the valley mouths, although no explanation can be suggested. The twin jetties of the harbor at Camp Pendleton are located a mile to the north of the San Luis Rey Station. Flying over these jetties has shown that sand is accumulating on both sides with somewhat of an excess on the north as would be expected from the current measurements in the Oceanside area.

Summary for Torrey Pines to North Oceanside. - Along the straight beaches in this central portion of the area of study, the observations showed great consistency in that all the dominant currents were clearly south. All of the stations had more south flowing currents than north, and 13 out of the 16 stations showed higher velocities for the south flowing currents. In general, less rip currents were reported than in the zones to the south.

Seasonally the currents show a decided north direction in the late summer, changing to an overwhelming south flow during the fall, winter, and spring but with a return to a considerable number of north currents in the early summer. Previous observations at Oceanside indicate a dominance of north currents in early summer, but the 12 months of special study showed somewhat more south currents.

San Onofre

Four stations were observed in the vicinity of the cove at San Onofre (Figure 11). The southern station is at the well-known surfing beach one mile south of the cove, and the other three are at the two ends and in the middle of the crescent-shaped beach of the cove. The general situation is quite different from the areas to the south. The average trend of the coast is north 60° west. As a result the most common wave trains which approach from the west or northwest hit the coast diagonally from the north. Waves coming from these directions are somewhat damped by Santa Catalina Island which lies 45 miles to the west. This is in contrast to the stations from Oceanside south where there is much less effect of Santa Catalina as can be seen from Figure 1. Surf Station, as the name indicates, was located at the surfing beach. Here the sand which has a median of 300 microns gives out at about low tide level, and a cobble and boulder bottom, with reefs, extends beyond. The


117° 35'
117°34'
SAN MATEO POINT
33° 23'
Hb = 3.5'
SAN ONOFRE
NORTH SAN ONOFRE
CRESCENT STATION
Hb = 3.75'
N
Hb = 4.1'
FENCE STATION
Hb = 3.5'
SURF STATION
10
20
30
33° 22'
30 = CONTOURS IN FEET
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER
1000 0 1000 2000 3000
SCALE IN FEET
= KELP
Hb = AVERAGE BREAKER HEIGHT
117° 35'
117° 34

LONGSHORE CURRENTS AT SAN ONOFRE

FIGURE II

average slope is very gentle so that the 10-foot contour is about 1,000 feet from shore, and the 20-foot contour is about 2,300 feet out. Because of this situation the waves start to build up well out from shore and develop a steep front which is maintained without complete breaking for most of the way to the shore. It is this condition which allows surfboard riding to best advantage. At Fence Station on the southeast side of the crescent beach the sand also extends only to low tide. The sand varies between 200 and 550 microns in median diameter. This station is of especial interest since the beach berm, unlike all other beach berms for which measurements are available in the California area, grows seaward during the stormy winter and spring season, and retreats during the summer and fall when waves are smaller. Crescent Station is at the head of the bay. Here the sand extends below low tide level. The sand median diameter is about 250 microns. The berm shows little fluctuation at this station. At North San Onofre on the north side of the crescent, the sand base is exposed by low tide and cobbles are found seaward. The sand has a median diameter of 300 microns.

It was impossible to estimate the breaker height at Surf Station. The heights show a progressive decrease from southeast and northwest in the three stations around the crescent beach. This is as would be expected, since the westerly swells hit Fence Station most directly and impinge with the smallest angle at North San Onofre.

As shown in table 5 the currents are more consistent in the San Onofre area than anywhere else. Observations at all of the stations show an overwhelming south trend. The times when north currents were observed at one or more of the stations were in the late winter and early spring instead of during the summer and fall when the southerly swell might have been expected to produce northerly currents at least at Fence Station. The current observations apparently do not provide

TABLE 5
San Onofre Currents

Station	Height of breakers	No. of days observed			Average velocity in knots		Number times velocity		Net
		N	S	Neut.	N	S	N	S	
Surf Station	3.5	3	14	3	0.30	0.41	.9	5.57	S
Fence Station	4.1	3	23	5	.55	.59	1.6	13.6	S
Crescent Sta.	3.7	3	18	6	.37	.47	1.1	8.5	S
North San Onofre	3.5	0	18	3	---	.50	--	9.0	S

any help in solving the enigma of the berm building at the unusual time at Fence Station. It had been supposed that the currents were moving north in summer and taking away sand from Fence Station and moving south in winter and thus piling up sand. So far as the observations went, no such arrangement was found.

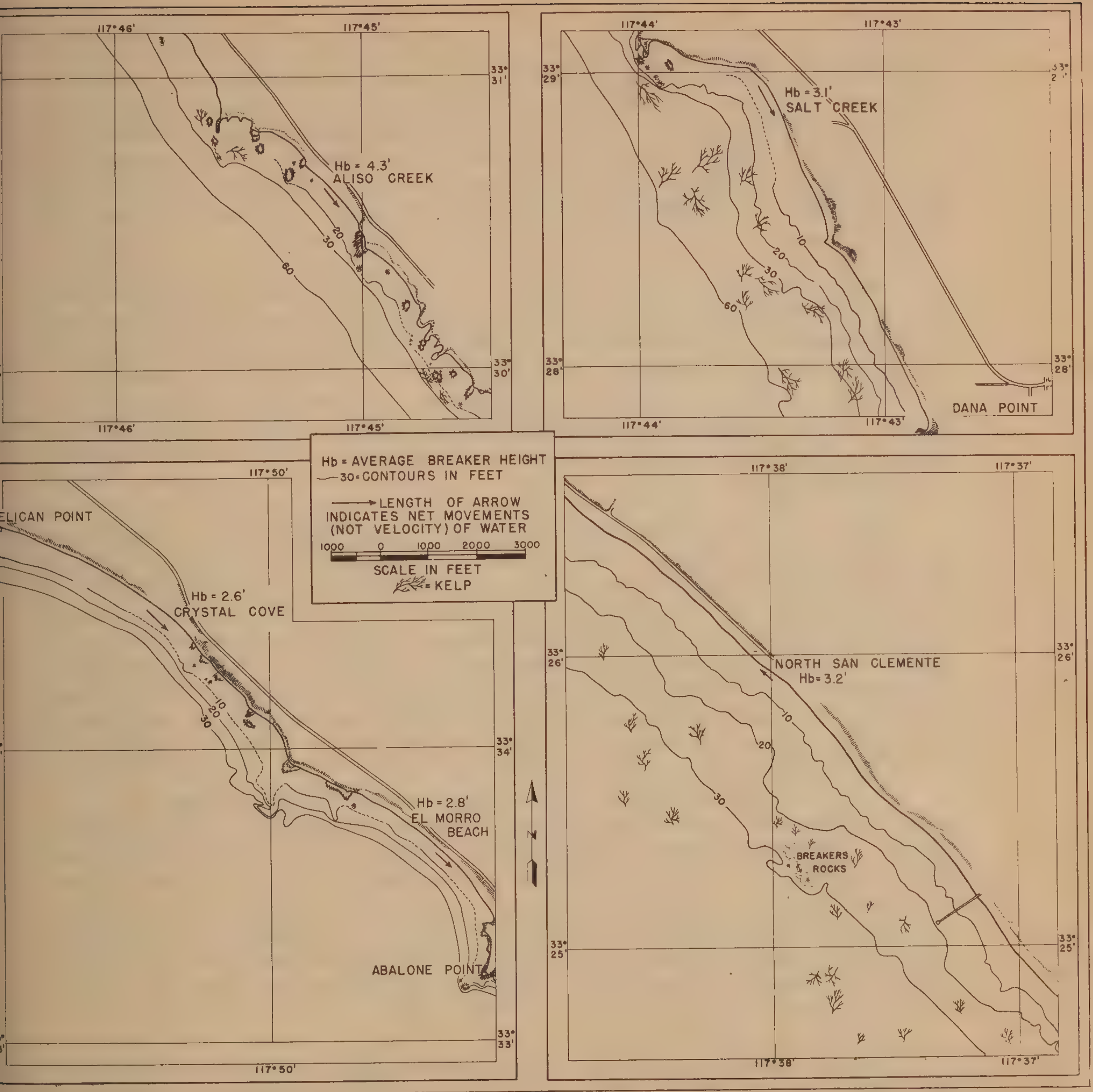
Scattered Stations, San Clemente to Crystal Cove

North of San Onofre five stations were chosen at scattered points between San Clemente and the Newport area (Figure 12). Four of these are in coastal indentations similar to that at San Onofre and the fifth is on a straight stretch of coast but is only a little over three miles south of Dana Point, the most pronounced headland in southern California between the La Jolla and Los Angeles areas. A sixth station in the lee of Dana Point at Doheny Beach was observed for a short time but the currents were so consistently weak or neutral that the station was abandoned. Table 6 shows the current relations at these five stations.

At North San Clemente the currents were measured near the spot where the main highway comes down to the shore north of the town. The locality is at a valley mouth. Sea cliffs exist to the north and south but are separated from the shore line by a relatively wide beach along which the highway runs north of the station. The submarine contours show a ridge and a reef just south of the station. The currents at North San Clemente are of special interest since this is the first station north of Scripps Beach where north currents were found to have an ascendancy in the product of the number of observations times the average velocity. Even the average velocity to

TABLE 6
San Clemente to Crystal Cove Currents

Station	Height of breakers	No. of days observed			Average velocity in knots		Number times velocity		
		N	S	Neut.	N	S	N	S	Net
North San Clemente	3.2	10	10	11	0.62	0.57	6.2	5.7	N
Salt Creek	3.1	5	15	8	.47	.45	2.3	6.7	S
Aliso Creek	4.3	11	11	8	.58	.72	6.4	8.0	S
El Morro Beach	2.8	8	16	8	.53	.50	4.2	8.0	S
Crystal Cove	2.6	6	9	11	.44	.69	2.6	6.2	S


117°46'
117°45'
33° 31'
33° 30'
Hb = 4.3'
ALISO CREEK
20
30
60
117°44'
117°43'
33° 29'
33° 28'
Hb = 3.1'
SALT CREEK
10
20
30
60
DANA POINT
Hb = AVERAGE BREAKER HEIGHT
30 = CONTOURS IN FEET
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER
1000
0
1000
2000
3000
SCALE IN FEET
= KELP
117°50'
ELICAN POINT
Hb = 2.6'
CRYSTAL COVE
10
20
30
33° 34'
Hb = 2.8'
EL MORRO BEACH
ABALONE POINT
33° 33'
N
117°38'
117°37'
33° 26'
33° 25'
NORTH SAN CLEMENTE
Hb= 3.2'
10
20
30
BREAKERS & ROCKS

LONGSHORE CURRENTS AT ALISO CREEK, SALT CREEK, CRYSTAL COVE, EL MORRO BEACH, AND NORTH SAN CLEMENTE

FIGURE 12

the north is somewhat higher. The reasons for this slight excess of drift to the north are not certain. It may be significant, however, that this station lies well south of a protruding point, a position which is comparable to that of the southern stations with north drift at Coronado Strand. Probably of more significance is the possible wave convergence behind the rocks south of the station. The rise of water level at the convergence probably produces a north current at the station.

Salt Creek is in a bay which is somewhat protected from the north by reefs and a projecting point. The station is at a valley mouth just north of a bluff. The sand has a median diameter of 200 microns. The currents are distinctly south in trend, with a 3 to 1 majority so far as number is concerned. This bay is somewhat similar to San Onofre where south currents are also pronounced. However, it is somewhat surprising that the projecting point at Salt Creek has not reversed the flow.

Aliso Creek station is located on a sand bar of coarse sand with a steep foreshore slope. The sand has a median diameter of 470 microns. The sand bar has been built across the mouth of Aliso Canyon, and there are rock promontories at less than a thousand feet to the north and south. Here the north and south currents are of equal number, but the south velocities are considerably higher so that south flow is favored. The breaker heights of 4.3 feet are greater than at any other station north of the Oceanside area. The beach has beautifully developed cusps which were reported consistently by the observers.

El Morro Beach differs from those previously described in having a prominent point to the south whereas there is a long beach to the north with only a small point. The beach is flanked by a low bluff which has a slight gap well to the north of the station. The waves here are over a foot lower in average height than those at Aliso Creek. The sand is much finer, having a median of 240 microns. Cusps were reported most of the year. The south currents are in the ascendancy here, although not to such a degree as to some of the other stations along this part of the coast.

Crystal Cove has only a slight indentation. The station is located on a crescentic sand bar at the mouth of a canyon. There is high ground on either side. The coastal trend is more to the east-west than is true of the stations farther south. Despite this trend, the number of southeast flowing currents is not much higher than those to the northwest, although the southeast currents have a much higher velocity. It will be noted that the number of neutral currents is unusually high. No reason for this fact is evident.

Newport-Balboa Area

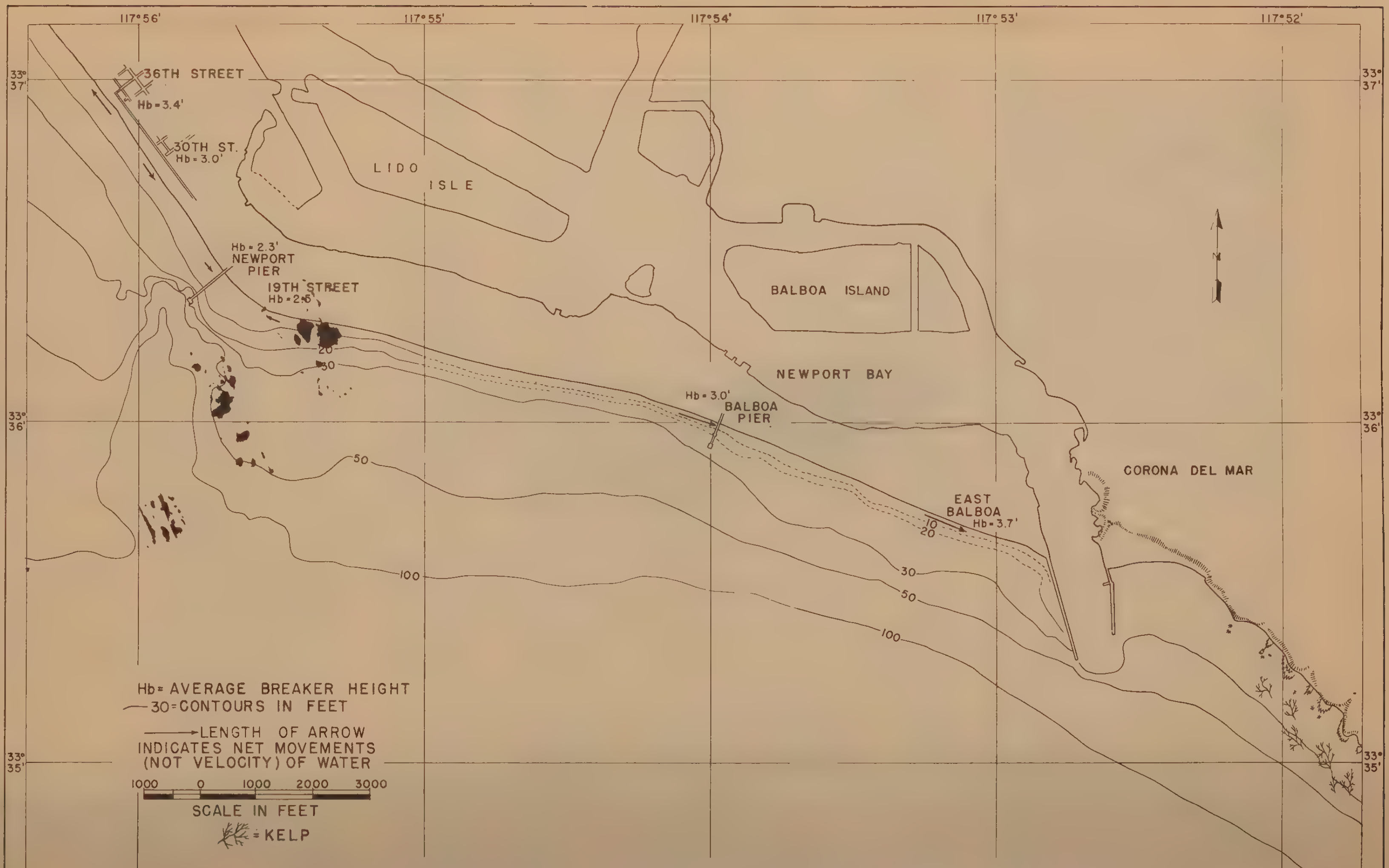
General description. - At Newport the long spit which extends for 4 miles east across Newport Bay was given six stations and two others were observed for the first two months (Figure 13). The locality has interest for several reasons; the submarine canyon which comes in almost to the shore just north of the Newport pier provides special wave refraction conditions (Figure 14), as does the long jetty at the east end of the spit; the coarseness of the sand with accompanying steep foreshore causes the waves to break almost on the shore and thus necessitates current study outside the breakers rather than inside as at the other stations; and the general east-west trend of the coast between the breakwater and Newport pier permitted the obtaining of data on a coast with this trend.

The waves show a decided relation to the divergence at the canyon head. As can be seen from Figure 13, Newport Pier is directly inside the center of the canyon although the northwest arm extends in past the pier. The pier station has the smallest waves and those at the 19th street station are almost as small as would be expected for waves coming from the west. The 30th street station has somewhat higher waves but not as high as at 36th street which is presumably near the center of the convergence north of the canyon. The 10th street station which was not continued after the first two months may have been close to a convergence on the east side of the canyon because the waves were higher here than at any other station except East Balboa. The reason for the high waves at East Balboa may be the outbend of the 30-foot contour off that station in relation to short-period waves which would cause some convergence. The most surprising thing about the waves was the considerable number of cases where the dominant wave orthogonals were seen approaching from the south. The sand at Newport is relatively coarse, ranging around 400 microns in median diameter.

Current system. - In relation to the submarine canyon the currents show the same general pattern that was observed at Scripps Beach. The currents are given in Table 7.

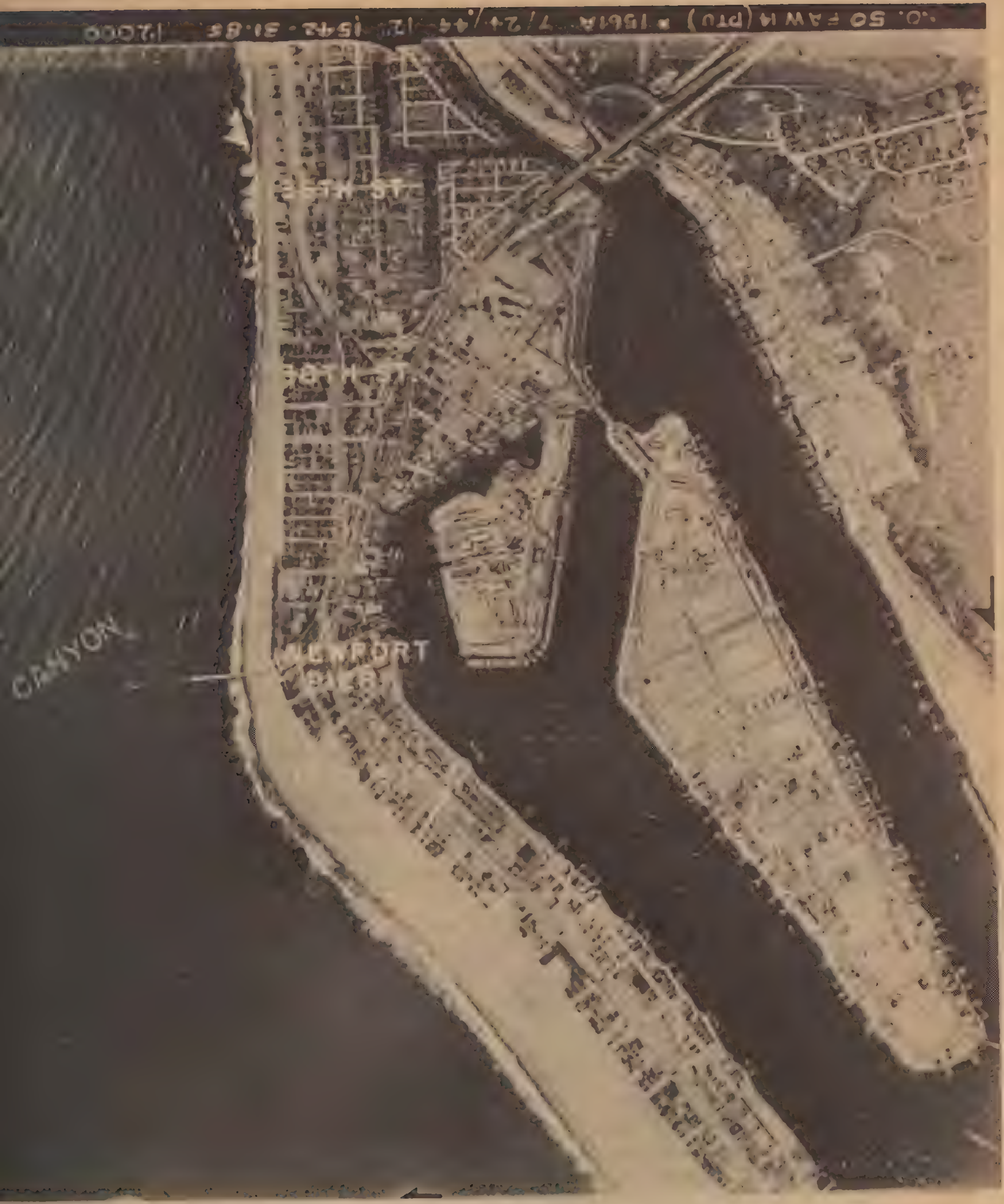
TABLE 7
Currents at Newport

Station	Height of breaker	No. of days observed N	S	Neut.	Average velocity in knots NW	SE	Number times velocity N	S	Net
East Balboa	3.7	6	7	16	0.29	0.77	1.8	5.4	SE
Balboa Pier	3.0	9	12	11	.60	.71	5.4	8.5	SE
19th St.,Newport	2.5	9	12	9	.63	.41	5.5	4.9	NW
Newport Pier	2.3	11	13	8	.60	.51	6.6	6.6	Zero
30th St.,Newport	3.0	8	14	9	.75	.53	6.0	7.4	SE
36th St.,Newport	3.4	13	9	5	.47	.46	6.4	4.1	NW


117°56'
117°55'
117°54'
117°53'
117°52'
33° 37'
33° 36'
33° 35'
36TH STREET
Hb = 3.4'
30TH ST.
Hb = 3.0'
LIDO ISLE
Hb = 2.3'
NEWPORT PIER
19TH STREET
Hb = 2.5'
BALBOA ISLAND
NEWPORT BAY
Hb = 3.0'
BALBOA PIER
CORONA DEL MAR
EAST BALBOA
Hb = 3.7'
10
20
30
50
100
Hb = AVERAGE BREAKER HEIGHT
30 = CONTOURS IN FEET
LENGTH OF ARROW INDICATES NET MOVEMENTS (NOT VELOCITY) OF WATER
1000
0
1000
2000
3000
SCALE IN FEET
= KELP

LONGSHORE CURRENTS AT NEWPORT AND BALBOA BEACHES

FIGURE 13



AERIAL PHOTOGRAPH OF NEWPORT BEACH. TWO WAVE TRAINS ARE SHOWN. LONG PERIOD WAVES FROM THE SOUTH AND SHORT PERIOD FROM THE NORTH. THE CANYON HEAD GREATLY REDUCES THE SOUTHERLY SWELL NARROWING THE SURF ZONE TO THE NORTH. NOTE ALSO THE CURVING OF WAVE CRESTS AT THE CANYON HEAD A SMALL RIP CURRENT IS SHOWN SOUTHEAST OF 19th STREET.

FIGURE 14

They are weak and variable at the canyon head. To the northwest of the canyon, the currents appear to flow away from the zone of wave convergence. To the east of the canyon, the currents are flowing east away from the canyon but in view of the east-west direction of the coast this would probably be the case whether the canyon was there or not. The north flowing currents are stronger than south currents at the stations in the vicinity and to the north of the canyon but the southeast flowing currents are stronger at the stations well east of the canyon. This difference can be explained by the change in trend of the coast since the angle of orthogonal incidence is larger for south approach at the northern stations and for west approach at the southern stations. In successive runs the currents changed frequently in direction and speed on both sides of the canyon head. At East Balboa the preponderance of neutral currents is striking. The measurements near the breakwater at the eastern tip of Balboa were discontinued because the currents were found to be essentially neutral.

Perhaps the most remarkable point about the Newport currents is that they were all measured outside the breakers, and yet they do not show any appreciable difference in velocity from currents measured on the same day at stations where the measurements were made in the surf zone.

Seasonally, currents in the Newport area are at variance with those in the other areas to the south. South currents were in excess from April through September and north currents during the other half of the year. The August-September currents had a pronounced southeasterly trend whereas directly afterwards in October and November the northwesterly currents were most abundant.

Summary and Comparison of the Different Areas

General considerations. - In summarizing the information from the preceding description of currents at the beaches of the southern 100 miles of the California coast, care had to be exercised in order not to come to false conclusions because of averaging quantities which were not comparable. For example, one might make a simple addition of the currents at a series of stations and come to the conclusion that the dominant currents along a certain coast were south, whereas complete information might have shown that all of the stations were exceptional and that the currents were dominantly north. It was, therefore, important to look for special reasons why the currents flowed in a certain direction and to compare cases where conditions were essentially similar. Causes of longshore currents were considered at the beginning of the paper.

Dominant current direction. - The dominant current direction for the southern 100 miles of California coast line can be computed from the available statistics in several ways. The total numbers of north and south current directions are thought to be of no great importance since the stations at Scripps Beach have more measurements than the others, and Scripps Beach happens to be an area where north currents dominate partly because of the submarine canyon. However, the total figures for whatever they are worth are 1,009 north and 1,003 south. Excluding Scripps the figures become 489 north and 723 south, that is, 40.4% north and 59.6% south. These figures also fail to be entirely representative of southern California since there were a few more observations in late summer when north currents were more common. Excluding the Scripps Beach observations, north currents dominated in only three months, August, September, and November. So far as stations are concerned, 28 stations had more days with north than south currents and 36 stations had more days with south currents. However, excluding the 17 Scripps stations this becomes 16 stations north to 31 stations south or about twice as many with dominant south currents. Multiplying the number of north and south currents by the average velocity for the two directions we find 25 stations with north dominant and 39 stations with south dominant. Again subtracting the Scripps stations this becomes 13 stations north to 34 stations south or almost 3 times as many south as north.

The preceding figures indicate the dominance of southerly currents in this stretch of coast. Consideration of the cases where north currents proved dominant shows that almost all of them can be explained as the result of movement away from a point of wave convergence. Such convergences can be looked for on one or both sides of a submarine canyon which has a head coming close to the coast and inside a submarine ridge. There are also indications that north currents prevail to the south of projecting points, although three stations on Coronado Strand proved to be definite exceptions to this rule. The projection formed by Morro Rock, north of San Luis Obispo in central California, has probably resulted in a north current since a spit has been built in that direction, forming the Harbor at Morro Bay. These north currents are presumably in part the result of counter currents set up by the projections. Probably, the north trend of the coast at the south end of Coronado Strand plays some part in the development of the north currents.

A special case where current directions are overwhelmingly in the same direction is found on either side of the entrance to Mission Bay. The predominance of currents flowing towards the bay entrance, even when the tide was flowing out, is clearly the result of the bar which exists off the bay and causes a deflection of the wave orthogonals toward the bay entrance on either side with the result that the orthogonals point toward the entrance. As explained previously this current must be compensated by strong outflow in the center during ebb tides.

It is interesting to note the statistical results obtained from compilation of north and south currents at all stations which are located on relatively straight coasts with essentially parallel submarine contours. All of these stations show a predominance of southerly currents. The total number is 156 north as against 289 south.

From this observation one can conclude that the building of jetties in this area will result in beach growth on the north side and beach erosion on the south side unless one of the special influences which has been discussed intervenes.

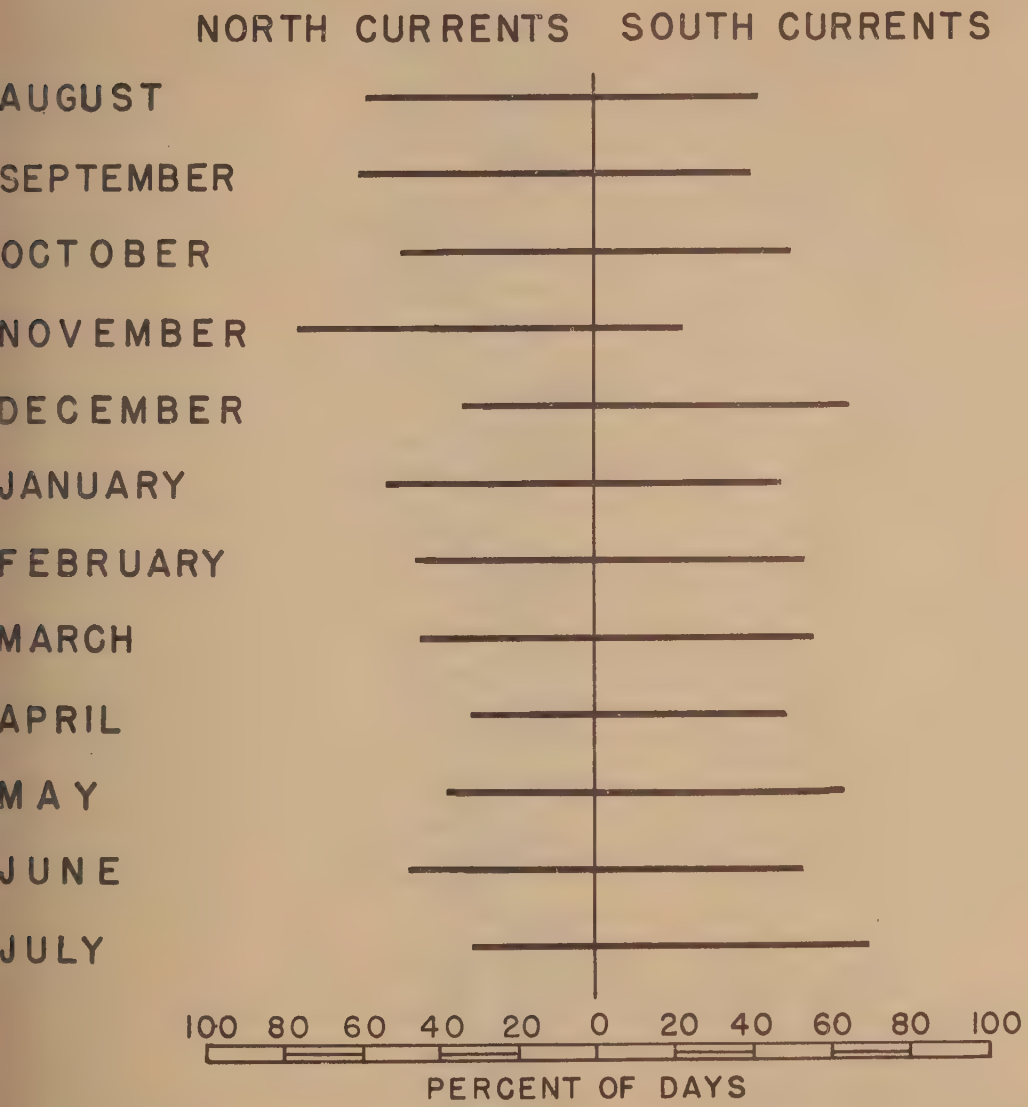
Seasonal variation in currents. - The variation of currents throughout the year in this area can be illustrated in several ways. Figure 15 gives the percentage of days of north and south observations for all areas in each month. Table 8 gives the percentage of north, south, and neutral currents for six pairs of months at the various groups of beaches. Illustrative of the day to day variation in the currents, Figure 16 shows the number of north, south, and neutral currents observed on each day of field study. The locations visited are indicated by the initials. The accompanying figures along the side indicate the agreement, half agreement, or counter direction of wave approach and current direction.

TABLE 8
Percentage Variation Seasonally of Current
Directions by Station Groups

Months	Coronado Strand			Mission Beach			Scripps Beach		
	N	S	Neut.	N	S	Neut.	N	S	Neut
Aug - Sep	43 (58)	31 (42)	26	64 (68)	29 (32)	7	55 (67)	27 (33)	17
Oct - Nov	64 (70)	27 (30)	10	49 (54)	42 (46)	8	57 (65)	31 (35)	12
Dec - Jan	21 (33)	42 (67)	37	25 (27)	69 (73)	6	55 (79)	15 (21)	30
Feb - Mar	27 (38)	44 (62)	29	44 (52)	41 (48)	15	48 (59)	33 (41)	19
Apr - May	42 (53)	38 (47)	20	37 (44)	47 (56)	17	43 (57)	32 (43)	25
Jun - Jul	54 (58)	39 (42)	7	21 (26)	58 (74)	21	51 (52)	47 (48)	2

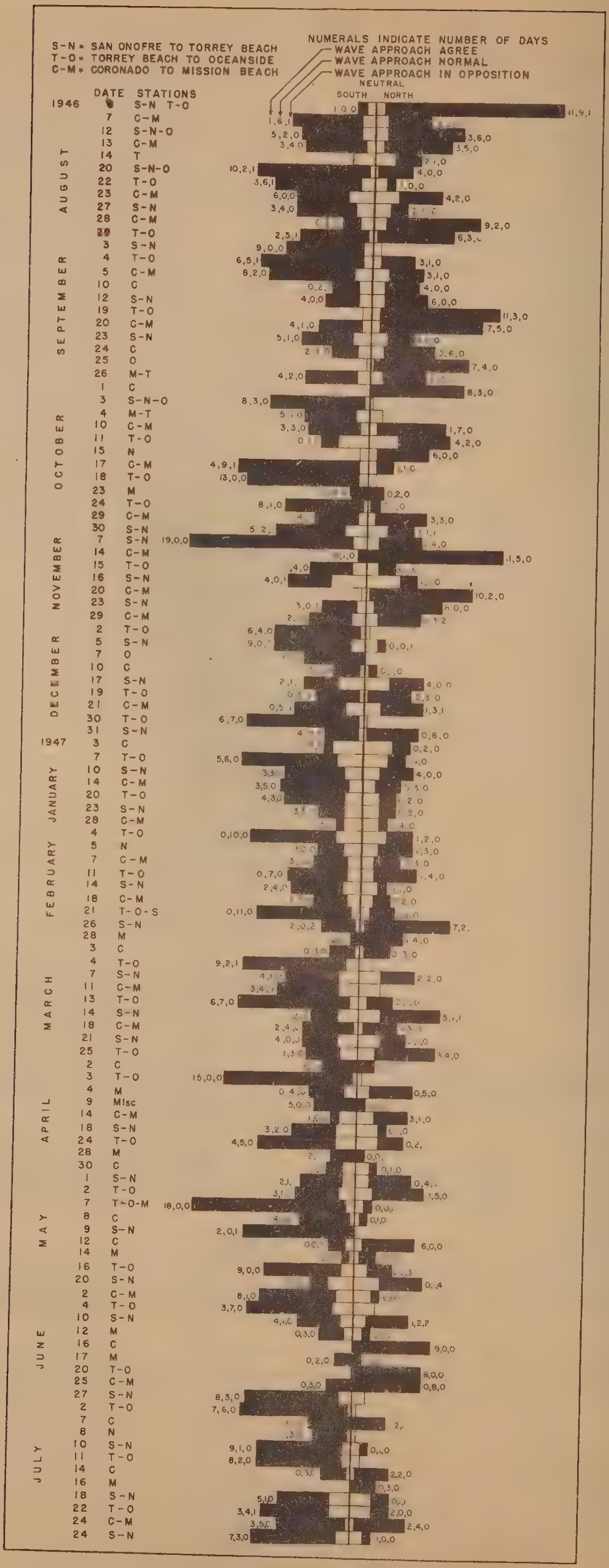
Months	Torrey to Oceanside			San Onofre to Crystal Cove			Newport Beach		
	N	S	Neut.	N	S	Neut.	N	S	Neut.
Aug - Sep	63 (72)	25 (28)	13	27 (32)	58 (68)	15	18 (27)	61 (77)	21
Oct - Nov	18 (22)	65 (78)	17	8 (11)	62 (89)	30	63 (82)	14 (18)	23
Dec - Jan	12 (14)	73 (86)	14	18 (28)	47 (72)	35	43 (57)	32 (43)	25
Feb - Mar	15 (18)	66 (82)	19	41 (49)	42 (51)	17	39 (72)	15 (28)	46
Apr - May	22 (25)	65 (75)	13	19 (27)	52 (73)	29	30 (38)	48 (62)	22
Jun - Jul	33 (40)	50 (60)	17	17 (22)	63 (78)	20	17 (25)	52 (75)	31

NOTE: Numbers in parenthesis are north-south percentages omitting neutrals.



MONTHLY TOTALS
OF
NORTH AND SOUTH CURRENTS

FIGURE 15



DAILY VARIATIONS OF LONGSHORE CURRENTS

FIGURE 16

Examination of the table shows that the seasonal variation is somewhat different in the different localities. The times of maximum north current are in August-September for Mission Beach and from Torrey to Oceanside, and in October-November for Scripps Beach, Coronado Strand, and Newport Beach, but in the San Onofre to Crystal Cove area, north currents show a maximum in February and March. South currents are for the most part dominant and stronger in winter, although at Scripps Beach and from San Onofre to Crystal Cove they show a maximum in June and July. Considered altogether the north currents for the southern California area are most common in the late summer and fall and the southerly currents all the rest of the year. However, data from other years indicate the possibility that the particular year of the observations was somewhat atypical in that there were more northerly currents in early summer in other years.

The daily variations (Figure 16) are instructive since they show what rapid changes take place in the area. In a considerable number of cases the currents shifted from being predominantly in one direction to predominantly in the other after an interval of a few days. In general, this rapid shift was not observed at the same beaches since the beaches were examined in rotation.

Relation of currents to direction of wave approach. - In the field, attempts were made to determine the direction from which waves were approaching. The field assistants, who made most of the observations, did not feel confident in all of these observations since many of them were made so close to sea level and the waves were often so much confused that it was very difficult to be sure of the direction of approach of the principal wave trains. However, attempts were made in all cases to distinguish north and south approaching waves or normal and crossing approaches, the last being the case where two sets of waves of approximately equal importance were coming from opposite directions and would thus tend to neutralize the currents. Table 9 gives some of the results from these observations.

TABLE 9

Approach of Waves Related to Current Direction

(Data exclusive of Scripps Beach)

Direction of wave approach	Number of observations	Percentage	
		Total	North to south relation
North	320	33.5	62.4
South	193	20.2	37.6
Normal	218	22.8	---
Crossing	224	23.5	---

This table, based on rather uncertain data, shows that the great bulk of the currents agree in direction with the direction in which the waves approach. It will be noted that the percentage of north and south approaches compares quite well with the percentage of north and south currents for the beaches (exclusive of Scripps). On the other hand there appear to be a considerable number of appreciable currents where the approach was normal and even a number of currents which appeared to flow in the wrong direction so far as wave approach was concerned. While some of these cases are no doubt explained as the result of faulty observation it seems likely that there are cases where the currents do not agree with the direction of wave approach. However, in view of the multitude of causes which have been suggested for the longshore currents, this is not surprising.

It was thought that the comparison of direction of approach and direction of current might vary in different localities. Table 10 shows some differences.

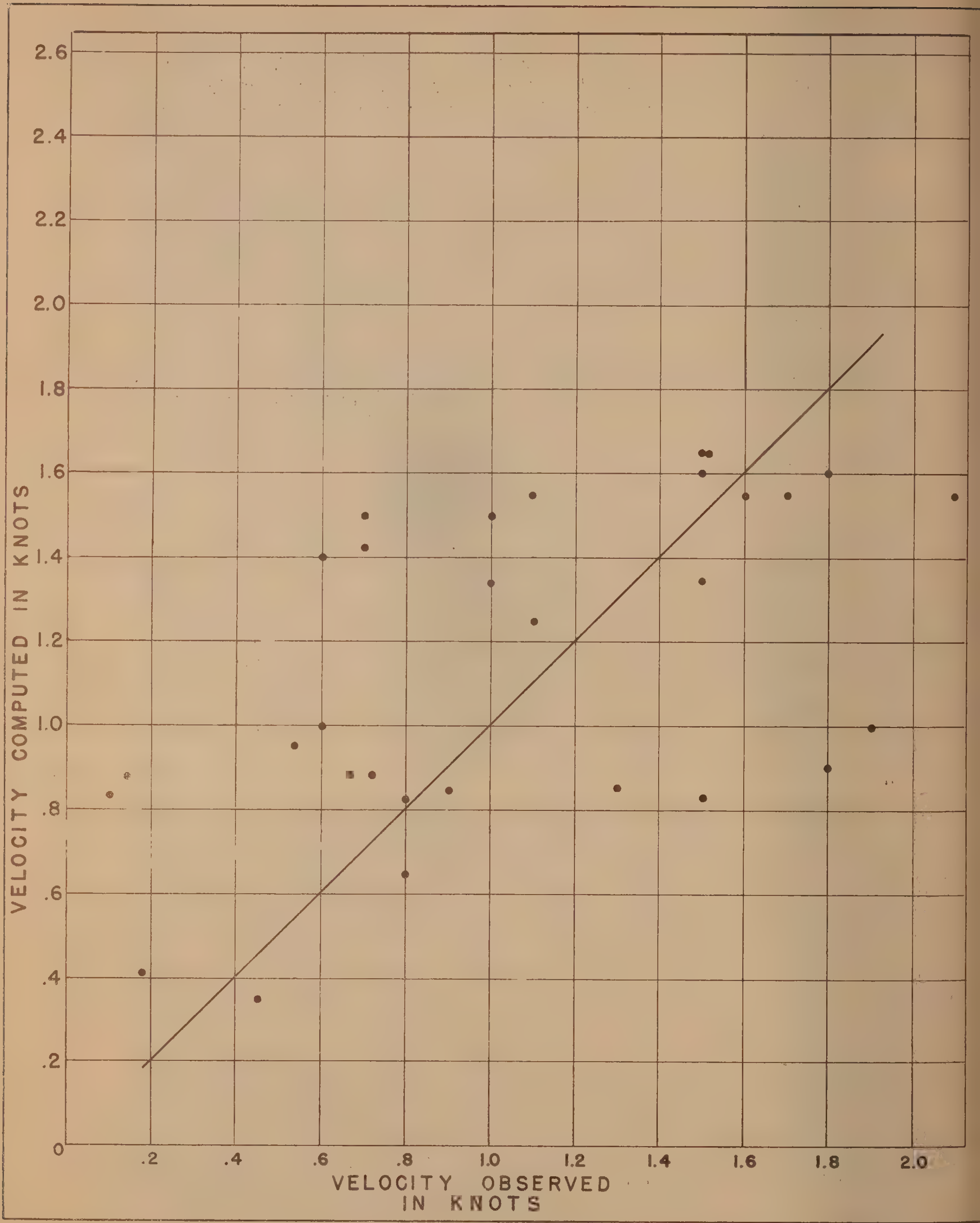
TABLE 10
Directions of Approach and Currents Compared in Different Localities

Locality	Per cent in agreement	Per cent in opposition	Neutral currents with N and S approach	N and S currents with normal approach	N and S currents with crossing approach	Number of observations
Coronado Strand	55.0	6.8	4.4	16.0	19.0	295
Mission Beach	40.5	5.0	6.6	19.1	28.6	136
Scripps Beach	50.0	11.0	6.3	20.0	12.8	508
Sorrento Beach	49.0	6.0	10.4	22.0	12.6	87
Oceanside	69.6	4.0	1.8	12.0	12.8	109
San Onofre	65.0	9.5	9.5	12.3	4.1	74
Newport	55.0	7.0	18.6	4.4	15.0	206

The data in this table has a number of interesting points. The place with the largest number of counterposed currents was at Scripps Beach where the submarine canyon would be expected to develop counterposed currents as explained previously. The large percentage of agreement at Oceanside is interesting since this was the area where W. H. Munk and others made measurements as a basis for their computations of longshore currents based on wave approach. On the other hand, it is hard to understand the relatively small agreement shown at Torrey Beach, where the submarine contours and the coast are essentially straight and parallel. Perhaps the most significant thing indicated by the table is that all of the beaches showed a considerable percentage of currents which did not agree with the direction of wave approach.

A convenient alignment chart was provided by Munk and Traylor (2) during the war as a means of predicting longshore currents for surf landing operations. Subsequently an improved chart was developed by Putnam, Munk and Traylor (4). These diagrams are only supposed to be approximate and to apply to conditions where the contours are parallel and the waves approach only in one direction. The charts take account of angle of approach, breaker height, wave period, and slope of foreshore. Since some of the data accumulated in the project described in this report included these various parameters, it seemed advisable to apply the most recent alignment diagram to them so as to compare observed and predicted currents. This has been done in Figure 17, all data coming from straight beaches with essentially parallel contours. It should be borne in mind that the angles of wave approach may not have been correctly measured and the length of time involved in current measurement may have been too small so that some allowance for these factors should be taken into consideration. However, one can not help being impressed with the lack of agreement which is found between computed and observed currents. One reason for the discrepancy comes from the great variation in the current observed in the surf zone at varying distances from shore. This is not taken care of by the diagrams. These data suggest, as did the entire study, that the prediction of rate of longshore currents is more complicated than may have been supposed and that no great reliance can be put on graphs or formulae because they are based on ideal conditions which rarely exist in nature.

Relation of longshore currents to breaker height. - The large amount of data available from these studies permits a correlation between breaker height and current velocity to be made with some assurance. Since the angle of incidence of the orthogonals plays an important part in the development of the currents it seemed advisable to separate waves into those with diagonal approach from one direction, those with crossing approach, and those with normal approach. Plottings were made of these groups. The medians for each half foot of wave height are given in Figure 18 for both diagonal approach and normal approach (that is, so far as the observor could determine). It will be noted that in both cases the velocity increases with an increase in breaker height although with some irregularity. A considerable spread was found in both groups as would be expected since so many other factors play a part in the net result. This spread of the current velocities for the diagonally approaching waves is indicated. The relation between the increase in the case of normally approaching waves is fairly constant. If these figures are representative, it could be predicted that, other things being equal, longshore



COMPARISON OF COMPUTED AND OBSERVED CURRENT VELOCITIES

FIGURE 17

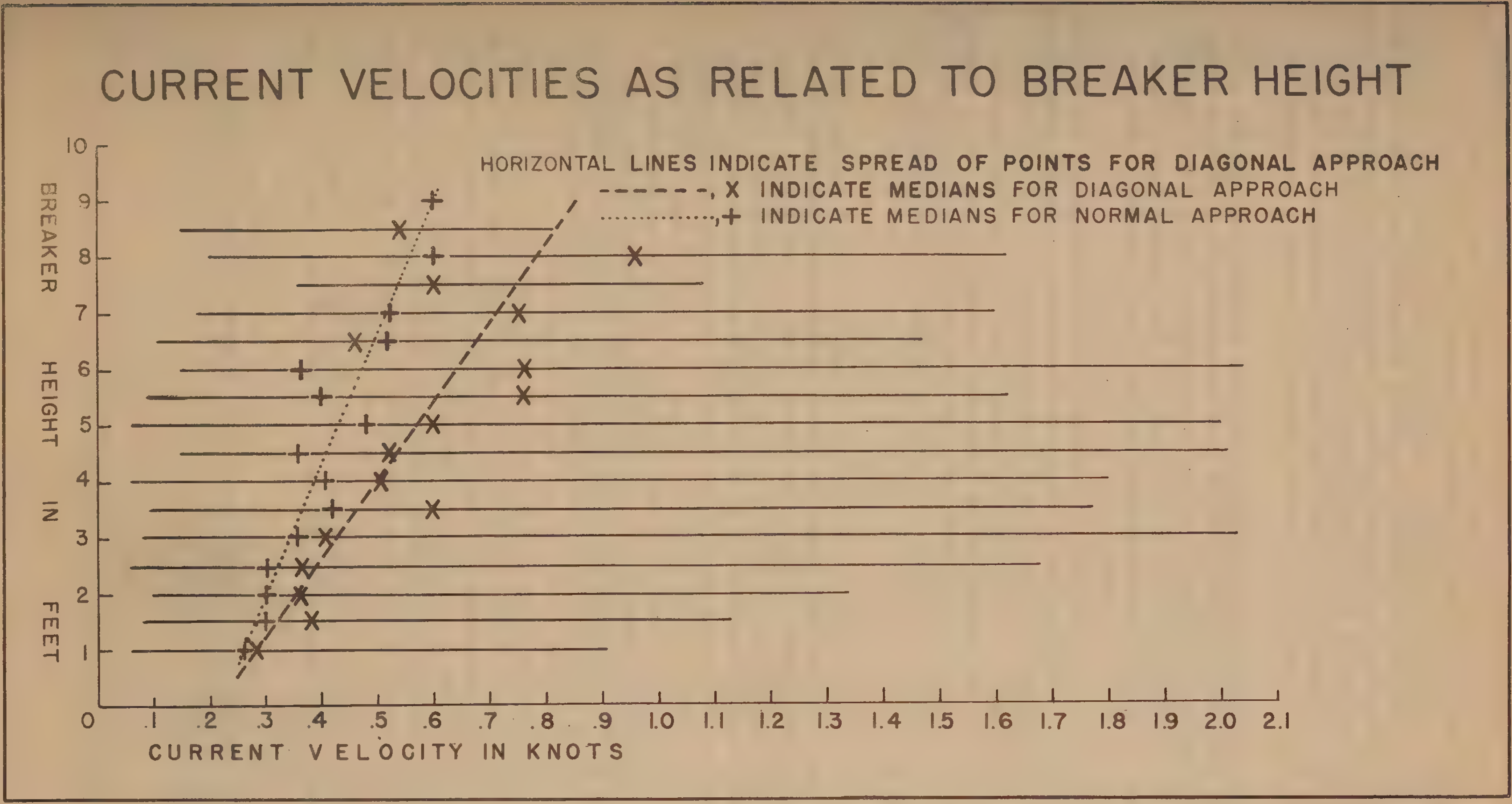

CURRENT VELOCITIES AS RELATED TO BREAKER HEIGHT

FIGURE 18

currents would be about one-third stronger on the average when waves are coming in with a diagonal approach. Naturally the angle of approach would be an important factor in the velocity. Figure 18 also indicates that very strong currents can be anticipated along the shore when large wave crests are approaching with essential parallel relation to the coast. Observations show that with this parallel approach the currents will tend to be more irregular since they will be more related to rip currents, although as stated previously, rip currents appear to be highly significant also during times of diagonal approach.

Currents in relation to tides. - In the narrow entrance to a bay the currents are predominantly tidal and in general flow into the bay with greatest velocity during the mid portions of the flood tide and out of the bay with the greatest velocity in the mid portion of the ebb tide. On the open coast the relation to tidal currents becomes much less definite. Measurement of the currents at the end of Scripps Institution pier over a period of several years showed that the current direction changed several times during the course of a day. The period did not exactly conform to the tides but appeared to be influenced by them. The direction of currents was clearly not related to the ebb and flood tides. For several days the current would flow south during flood tides and north during ebbs and then would gradually change until the reverse was true. The flow was always longer in one direction than the other.

The effect of tidal currents could be measured at Mission Beach, where a station was located near the north entrance to Mission Bay. Here,as described previously, the dominant current was south towards the entrance. Due to the outflow during ebb tide one might expect north currents during that stage. Actually, the percentage of north flow observations was as high during flood tide as during ebb tide, but the net velocity during flood tide was 0.35 knots south whereas it was only 0.12 knots south for the ebb tide. These observations show that the tide had much less effect than the diagonal approach of the waves which as explained previously had been influenced by the presence of a bar which extends somewhat north of the station.

The relation of the tide to longshore currents was tested on the open coasts by 8-hour runs over the stations of the same beach in five areas. These runs were made at the time of the spring tides. The tidal factor was further tested by making runs at flood for an overall result the currents under conditions of diagonal approach were plotted against stage of the tide under two groups of breaker heights.

The 8-hour runs showed that the currents shifted extensively when repeated at the same station, but, so far as could be determined, without any relation to the tide. For example, during flood tide three successive measurements often showed a shift from north to south and back again to north. These shifts were probably related to shifts of the eddies associated with rip currents and certainly were not tidal.

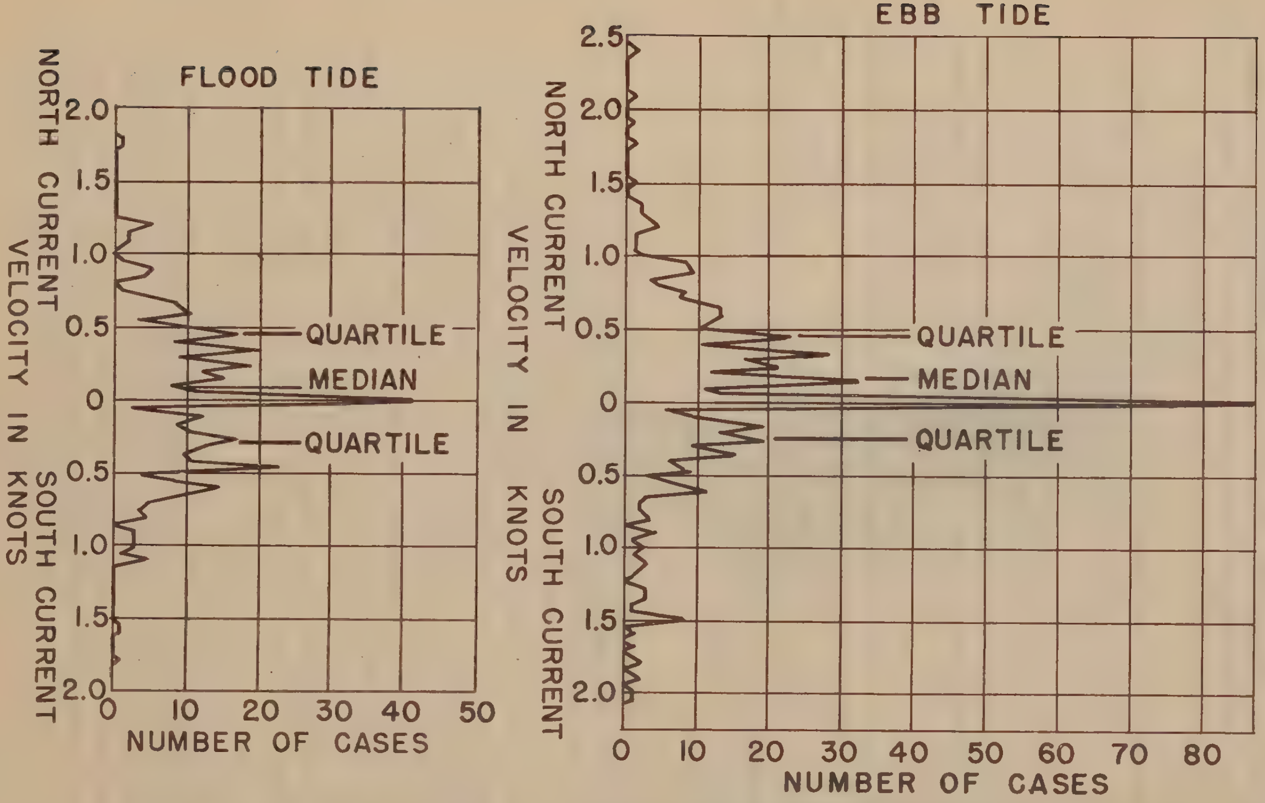
Plotting of the direction and velocity of the currents for the first five months of observations for both ebb and flood tides (Figure 19) shows that the median velocities and the quartiles are almost exactly the same for the two stages. The same was true of runs made at ebb and flood tides on the same day. There are more neutral currents in the ebb tide group but the difference does not seem significant.

Comparison of the currents at the same station between runs made at low tide and at high tide on the same day (Figure 20) showed that 64 per cent had become weaker at low tide, 28 per cent had become stronger, and 8 per cent had not changed as much as 0.05 knots. The median of the change was 0.27 knots weaker at the low tide.

The plotting of all measurements, where there were diagonally approaching waves from one direction, with height of tide as ordinate and the current velocity as abscissa shows no particular relationship. However, dividing the data into a series of graphs showing breakers of 2 to 3.5 feet for both north and south approach and the same for breakers of 4 to 6 feet produced some significant relations. The average velocities for four ranges of tide heights were plotted for the four conditions. The lines joining these points (Figure 21) all indicate maxima at low and high tide and minima at intermediate tides. The average velocities for low tide and high tide observations show little difference, tending to contradict the suggestion from the daily measurements that there are changes between low and high tides. There remains some likelihood that the longshore currents are increased at the time of highest tide and lowest tide. More tests would be desirable to check this point before coming to a definite conclusion.

Longshore currents in relation to submarine topography. - In discussing the cause of longshore currents, the effect of submarine ridges and submarine canyons was mentioned. Repeating briefly, it appears that the most important current effect comes from the convergence of waves onto ridges or on the flat on either side of a submarine canyon (Figures 6, 7, 13, and 14). The convergence appears to produce a rise in sea level at the point of the highest breakers and this rise is relieved by a flow to either side which may attain high velocity. Near the canyon head another type of current has been detected at La Jolla Canyon which moves away from the canyon center evidently due to the diagonally approaching waves which result from the divergence over the canyon along Scripps Beach. This current is weaker than the flow away from the convergences.

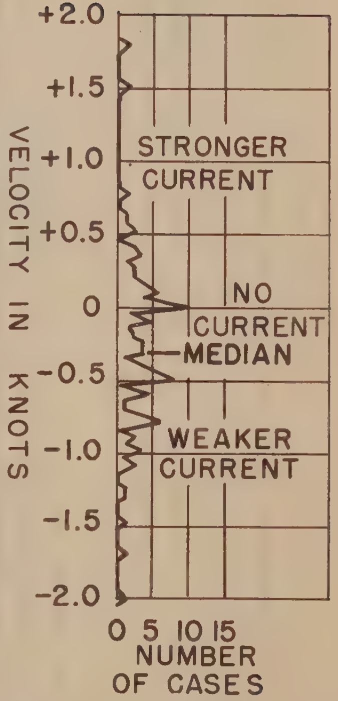
Surface and bottom components of longshore currents. - During most of the field work which is described in this report only the longshore components of the currents was measured. Drift bottles were used, which gave only the surface movement and at times the bottle had to be thrown seaward during the observation because it surfboarded in on some of the waves getting into too shallow water



MEDIAN AND QUARTILE EXCLUDE ZERO CURRENTS

CURRENT DIRECTION AT FLOOD AND EBB TIDE

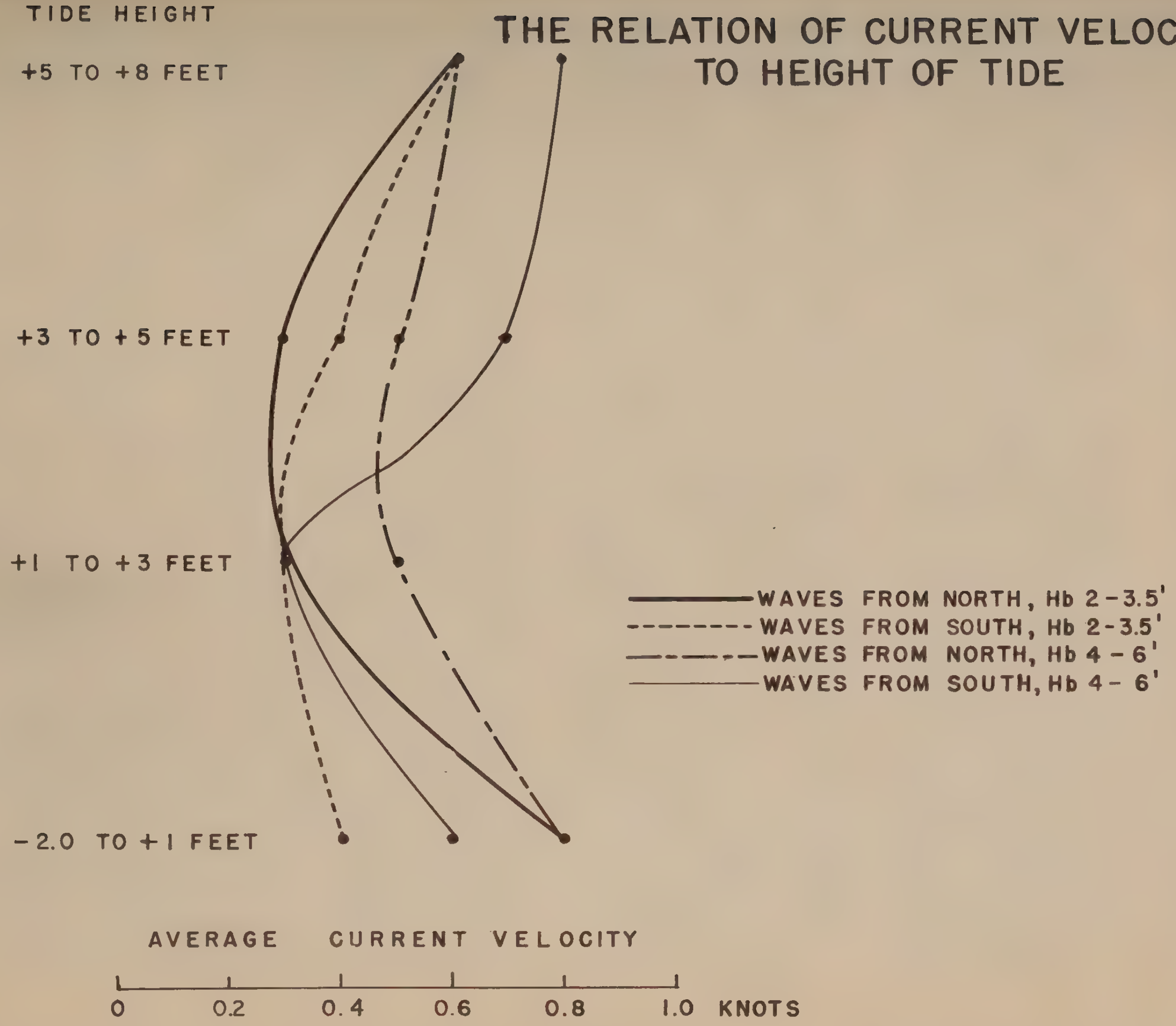
FIGURE 19



CURRENT CHANGES BETWEEN HIGH AND LOW TIDE AT SAME STATIONS ON SAME DAYS. (DOMINANT CURRENT FOR DAY TAKEN AS STANDARD)

CURRENT VELOCITY AT HIGH AND LOW TIDES

FIGURE 20



THE RELATION OF CURRENT VELOCITY TO HEIGHT OF TIDE

FIGURE 21

for effective currents. Toward the end of the work a weighted ball was used which was made to exceed sea water slightly in density. Measurements by this method were made largely by Commander R. Panzarini. The method showed a very large degree of accordance with the floats so far as direction was concerned. Average longshore components of the velocities were about four-fifths of those obtained by the drift bottle method.

Recently a series of measurements with the ball, with suspended triplanes and with dye marker have indicated the nature of variation from surface to bottom in the surf zone at Scripps Beach. This information will be the subject of another report, but it can be stated here that the variation between top and bottom currents is not of a large order. In areas of strong longshore currents both the top and bottom currents move essentially parallel to the shore. However, in approaching rip currents, the bottom water appears to turn seaward before the surface water is involved.

Currents in and outside the breakers. - Except at Newport the currents measured during the year's operation were inside the breakers, but at Newport as explained previously, the steep descent of the foreshore results in the waves breaking almost at the shore line so that the currents had to be measured beyond the breakers. Results at Newport seem to indicate that the currents have the same strength in comparison with wave height as at other stations. The relation of current to direction of wave approach is similar to the other stations. In fact, as shown in Table 10, the currents agreeing with wave approach are greater in percentage at Newport than at three of the beaches and less than at three other beaches.

While the newport area results might suggest that there is no particular difference inside and outside breakers, actual measurements at Scripps Institution pier and at Crystal Pier in the Mission Beach area show a definite difference. At Scripps pier the currents inside the breakers had an average velocity of 0.51 knots for 95 north measurements and 52 south measurements, whereas directly outside the breakers during the same period the currents had an average velocity of 0.12 knots for 82 north measurements and 78 south measurements; that is, average current velocities obtained were 4 times greater inside of the breaker than outside. At the end of the pier, which is on the average about 500 feet outside the breakers, the velocity during this period was similar to that directly outside the breakers, being 0.13 knots for 83 north currents and 77 south currents. At Crystal pier in the Mission Beach area the average velocity inside the breakers was 0.55 knots for 26 north currents and 23 south currents. Outside the breakers during the same period the average velocity was 0.23 knots for 15 north currents and 7 south currents, that is 2.4 times as fast inside as outside. Boat measurements have also indicated that currents outside the breakers are much weaker than those inside.

Daily current directions measured at the same time inside and outside the breakers showed agreement in direction at Scripps and

Crystal Piers in 57 per cent of the cases and opposition in 22 per cent. The remainder showed a neutral current inside or outside the breakers. The agreement at Crystal Pier is better than at Scripps with 63 per cent and opposition only 17 per cent.

Conclusions

The conclusions from this large mass of data must be somewhat tentative since the measurements had to be made rapidly in order to cover the long distances and the currents may have been temporary in many cases rather than representative of the day or period between observations at the same place. However, so far as is known, the study includes more data and was continued over a longer time than any other current observations in the surf zone. Furthermore, the detailed observations which the writer and his group have made subsequent to the year of wide-ranging observations have served to justify most of the main conclusions which appear to come from the larger mass of data. Also, there is no doubt that there are definite patterns to the observations which agree with known causes.

The outstanding conclusion from the study is that currents tend to flow in the direction in which the main wave trains are approaching the coast. Almost seven times as many currents were observed to flow in the direction of the principal approaching wave train as in the opposite direction. On the other hand, there are various other important causes of currents and undoubted evidence of strong currents has been obtained under conditions where the angle of approach was so close to normal that the angle of incidence could not have been the principal cause. There seems to be little doubt that current velocity is clearly related to the heights of breakers and that there are strong currents of variable direction during times when large breakers approach normal to the coast. These currents are associated with eddy circulation and rip currents which in turn appear to be due to the piling up of the water at certain points or in certain zones with resulting long-shore flow away from these points of convergence. This convergence is best developed in positions of irregular bottom topography, but is also developed by minor irregularities along straight coasts with essentially parallel submarine contours. Currents vary rapidly in velocity and even in direction according to the variation of breaker height and the shifting of position of rip currents.

The times when no appreciable longshore currents were observed appeared to be most numerous in early winter, possibly because this was a period of rather continued calms. Localities with a high percentage of neutral currents were those near the points or jetties at the end of a long straight beach. Rip currents were most common in areas at moderate distances from points of wave convergence and least common along straight beaches with parallel submarine contours.

Under conditions of waves approaching diagonally to a relatively straight beach with parallel submarine contours, the typical pattern of longshore currents is believed to be indicated in Figure 22. Obviously, the velocity of the current will vary in relation to the distance from the seaward moving rip currents and to the varying strength of the rips as well as in relation to other factors such as distance from shore.

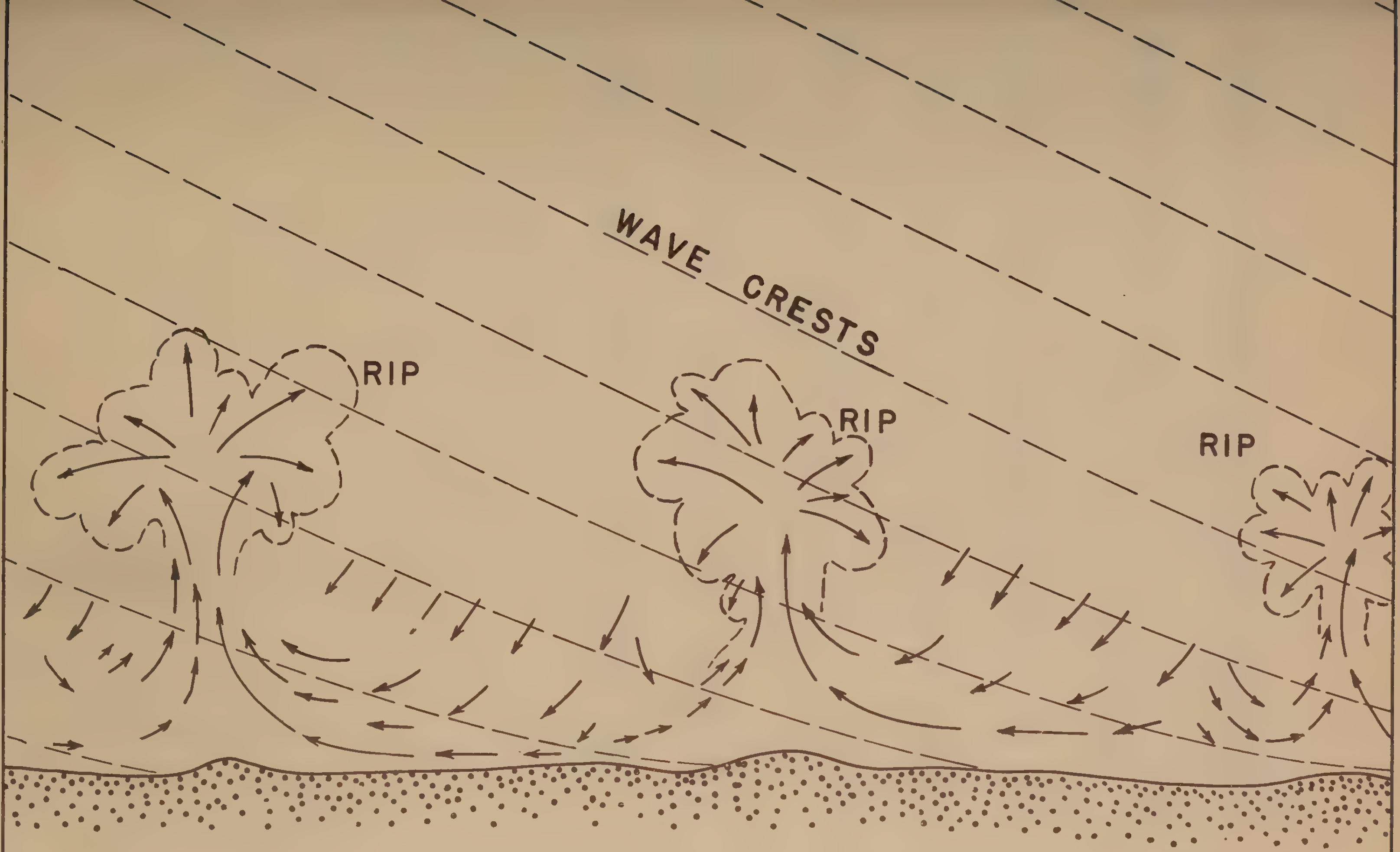
Longshore currents are decidedly faster inside of the breakers than outside. However, in places where there are steep beaches and waves break directly along the shore, the velocities outside the breakers, but very near shore, are comparable under the same wave conditions with those inside the breakers along more gently shelving beaches. Limited observations indicate that inside and outside of breakers currents flow in the same direction almost three times as often as in opposite directions.

Along the southern 100 miles of the California coast the conclusions seems to be justified that the dominant direction along the long straight stretches of coast with parallel submarine contours is to the south, but that even in these places a north current is more common during portions of the summer and fall. The prevailing southerly currents might have been predicted from storm track charts which show the prevalence of the storm centers to the west and northwest of southern California such as would bring waves with southward components of energy. However, the storm track charts have no data concerning southern hemisphere disturbances and the present study apparently indicated the importance of the latter in producing the seasonal northerly currents.

There appears to be evidence that north currents dominate for the year south of projecting points although this is not true of all places as shown by the measurements at Coronado Strand. North currents are also found on the north side of submarine canyons where the circulation is dependent largely on the wave convergences which develop on the sides of the canyons and is due in part to the divergence of the wave pattern over the canyon head. These canyon effects, so far as could be determined, apply only to cases where the canyon extended into shallow water near the coast. The canyon effects may be quite different along coasts where the wave trains approach at a small angle as is the case west of Santa Monica.

Acknowledgments

The field observations were made largely by assistants at Scripps Institution with Dr. B. Sayner in charge of the field party during most of the work. Participation by the writer was limited to a few trips because of other commitments. Commander R. I. Panzarini of the Argentine Navy, a graduate student at Scripps Institution, made some special observations which have proven helpful. The analysis of the field data was made by the writer with the help of Mrs. Jeanne Carritt, D. B. Sayner, Bob Wisner and Ruth Yound. Many helpful suggestions have been made by W. H. Munk and D. I. Inman.


WAVE CRESTS
RIP
RIP
RIP

RELATIVE CURRENT VELOCITY SHOWN BY LENGTH OF ARROW

FIGURE 22

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Contribution No. 457

The Generic Status of Living Oysters and the Scientific Name of the Common American Species

GORDON GUNTER

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The Generic Status of Living Oysters and the Scientific Name of the Common American Species[1]

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INTRODUCTION

Species of oysters in the family Ostreidae are found over the world along the shores of all continents (excepting Antarctica) and some oceanic islands. Oysters are an important seafood and their shells are useful for various purposes. For that reason they have been extensively studied, and the oyster has been called the scientifically best known marine animal in the world (Clark, 1920; Nelson, 1938). Nevertheless, the proper generic name of several species, including that of the common American oyster, has never been commonly used or, in the case of most species, assigned. There are several reasons for this situation. The ordinary oyster biologist is not a taxonomist. The information which permits or, more correctly, necessitates a taxonomic revision has only recently been acquired. The conchologists have been notoriously concerned with shell characteristics and, since the oyster is one of the most variable animals in the world so far as shape of the shell is concerned, this has led to confusion in various ways.

In this paper I propose to clarify somewhat the generic status of the oysters of the world by considering taxonomic questions in the light of recently acquired biological knowledge. The present study leads to recognition of the two distinct groups of species of common oysters as *Ostrea* with *O. edulis* as type and *Crassostrea* with *Ostrea virginica* as genotype.

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SHELL CHARACTERISTICS OF OYSTERS

It is difficult to separate genera and exceedingly difficult to separate species of oysters on the basis of shell characteristics alone. Yet these characteristics are all that are available to the paleontologist and they are practically the only ones used by conchologists working on living species. The living American oysters on the reefs and different types of bottoms along the Atlantic and Gulf coasts of the United States vary a great deal. A replica of many living species of Ostreidae, so far as shell characters go, can be found there. Shells may be ridged, convoluted, plicated, fluted at the edge or varied in many ways. These facts have long been known to oyster biologists. I have shown (Gunter, 1938) that *virginica* may be wider than long or 2.5 times as long as wide. Nelson (1938, p. 58) says, "I am in full sympathy with Orton's hesitancy to accept specific designation in *Ostrea* on shell characters alone. In my large collection of shells of *virginica* are some which fall well within the range of variation of the shells of *edulis, gigas, lurida, angulata,* and *frons*. In one instance a small flat white shelled *virginica* which I dredged alive from the low salinity area of upper Delaware Bay, was identified from the shell as a *Spondylus* by one familiar with this genus and of associated animals in subtropical America.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 457.

"It is not proposed that shell characters be abandoned in the classification of oysters, but it is suggested that in conjunction with the shell the anatomy of the soft parts, which after all create the shell, and the physiology and the ecology of this pelecypod constitute a more adequate basis for sound taxonomy. This is certainly true of any species in which the shell is subject to such profound modification by environmental influences as is that of the oyster."

McLean (1941) discussed the extensive shell variations of oysters and the relationship between the soft anatomy and shell shape, as set forth by Nelson (1938). He stated that there are many more "categories" of oysters "than there are valid entities to fill them."

Ranson (1942), who has contributed more than any other worker to the understanding of the relationships of living and fossil oysters, recognizes clearly that external shell characters do not differentiate oysters. He states, ". . . the distinction of genera based on sculpture of the shell, . . . is artificial."

Several conclusions can be drawn from this state of affairs. There is little doubt that the genera and species of oysters have been multiplied unnecessarily. The conservative view seems to be justified. Taxonomists working with the Ostreidae must emulate the fisheries biologists, using large and "adequate samples" and analyzing large volumes of data statistically, as other modern taxonomists are doing, before the variations of species are properly comprehended. Lastly, it should be realized that the only people who have a right to use only part of an animal, such as the shell, to describe a species are the paleontologists. The paleontologists have only the shells to work with and these are even more difficult to relate to modern species and genera than the living groups are to relate to one another, on the basis of shell character alone. Therefore, fossil genera will be largely ignored here in discussing living genera of Ostreidae.

Nevertheless, a few shell characteristics are constant or more generally so than others. Oysters with a promyal chamber are more deeply cupped than oysters lacking this feature and have the muscle attachment farther removed from the hinge. These facts should be of some help to paleontologists in determining whether genera, especially the more recent genera, are related to modern types. The denticles along the anterior edge of the valves of some species, such as *Ostrea cristata*, of the South Atlantic and Gulf coasts, are constant.

McLean (*op. cit.* p. 2) says the form of the beaks and the hinge margin, the sculpture of the inner margin of the valves, particularly at the hinge and immediately on either side of it, and the form and position of the muscle scar seem to be the shell characters of most taxonomic importance. The last character is certainly important and the others possibly less so.

With these facts in mind we can proceed with examination of the genera of living oysters.

BIOLOGICAL REASONS FOR SEPARATING LIVING OYSTERS (GENUS OSTREA) INTO TWO GENERA[1]

It has long been known that the European oyster holds its fertilized eggs through most of larval development, while the American oyster sheds its eggs directly into the water where fertilization and larval development take place. Orton (1928) first pointed out that there are two distinct types of oysters and that all living species belong to one or the other. In type 1, "the shell is subcircular, the egg is large; adult larviparous, the individual is hermaphrodite; spawning occurs at medium temperature, round about 15° C; and the species flourish in temperate regions." In this group he included *Ostrea edulis,* the oyster of Europe, *O. lurida,* the Olympic oyster of the North American Pacific Coast, and *O. angasi* of Australia. In type 2 oysters "the shell is elongated . . .; the egg is small; the adult nonlarviparous, the individual of one sex only; spawning occurs at moderately high temperature, round about 20° C, and the species flourish in subtropical or tropical regions." In this group he included the common American oyster, *O. virginica,* the Portuguese oyster, *O. angulata,* and the East Indian species, *O. cucullata.* He suggested that the two types of oysters be given subgeneric or generic rank, the first known as *Ostrea* and the second as *Gryphaea.* However, Orton preferred his own new terms *Monoeciostrea* and *Dioeciostrea* for types 1 and 2, respectively. The first term cannot replace *Ostrea,* which is well established. The last term is also a synonym as will be shown. In addition, it has been shown by Amemiya (1929) and Burkenroad (1931) that type 2 oysters change sexuality and Orton (1927) himself had shown that *O. edulis* also changes. Therefore, Orton's terms are not only nomenclaturally unnecessary but wrong in their implication. The latter fact was unknown at the time Professor Orton wrote.

The supposed difference in distribution stated by Orton (1928) was questioned somewhat by Nelson (1938), who pointed out that *virginica* endures freezing temperatures for several months of the year on the United States east coast, that *O. lurida* of the Pacific cannot endure freezing temperatures, and that *O. cristata* lives along the U. S. South Atlantic and Gulf coasts. These differences are somewhat resolved if it is remembered that type 1 oysters are largely marine, while type 2 oysters are estuarine. Therefore, type 1 lives in a more stable environment, while type 2 has been subjected to and is apparently better adapted to wider changes of temperature, salinity and turbidity. The difference in spawning temperatures are not so clear as Orton indicated. Type

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[1] This question has been briefly discussed previously in abstract form (Gunter, 1948).

1 oysters do seem to extend into higher latitudes. *Ostrea cristata* Born, extends from North Carolina to Brazil; *O. stentina* Payraudeau, and *O. edulis* Linnaeus, live in the Mediterranean. Other type 1 oysters live in the subtropics and tropics. The supposed differences in distribution may not actually hold true and should be investigated further.

Elsey (1935) found that the gills of *O. lurida* (type 1) oysters have very large ostia, through which the large eggs must pass during spawning. Hopkins (1936) verified that eggs pass through the gill ostia. It appears that large ostia in the gills is another character differentiating type 1 oysters from type 2 oysters.

Nelson (1938) discovered the significance of the promyal chamber, a distinct anatomical feature of type 2 oysters, which is essentially a second epibranchial chamber. He showed that it is a feature of the estuarine species, living in muddy waters and stated that it enabled oysters to cleanse themselves of sediment. Type 1 oysters live in clearer and more saline waters farther offshore. Oysters with a proymal chamber have the muscle attachment farther removed from the hinge of the valves. The valve is also more deeply cupped than in type 1 oysters. Nelson (*op. cit.*) agreed with Orton on the importance of the differences of the two types of oysters and said that those of type 2 should be raised to the generic rank. He placed them in the genus *Gryphaea*.

Ranson (1939, 1942, 1943) has shown in a convincing and very interesting series of papers that type 1 and type 2 oysters, which he calls *Ostrea* and *Gryphaea*, respectively, are clearly separable on a basis of characters of the prodissoconch shell, chiefly of the hinge. In addition he has shown that *Pycnodonta* may be separated as a third genus, on the same basis. The important bearing of Ranson's work on the classification of oysters will be discussed further on. For the time being we are only interested in the genus *Ostrea*, of most workers, which really includes two genera.

Table I shows the differences between type 1 and type 2 oysters. These characters merit some further discussion, and for that purpose will be numbered 1, 2, 3, etc., from top to bottom of the table.

The first character is based on an observation of my own, which will be obvious to most oyster biologists. There are a few really large oysters in the type 1 group and some of them, such as *Ostrea cristata* and *O. lurida*, are very small. On the other hand the Portuguese oyster, *angulata*, the American *virginica* and the Japanese *gigas*, of type 2 are very large, the largest attaining a length of 8 to 10 inches and, in exceptional cases, more.

Characters two, three and four are all interdependent. The first two were pointed out by Orton (1928). The last was noted by Elsey (1935) in *O. lurida* and so far as the literature shows the observation has not been confirmed for other species. However, it is highly probable that all larviparous oysters have large gill ostia and the character is included here for the sake of completeness.

Characters five to eight are also interdependent. They were discussed above except for pigmentation of the muscle scar. In addition the presence of the promyal chamber may account for the greater elongation of the type 2 oysters. At any rate these oysters seem to be not so round as species with the muscle nearer to the center of the shell. I am indebted to Dr. P. Korringa for pointing out that the common type 1 oysters of Europe and America do not have a pigmented muscle scar. Conversely the muscle scars of type 2 oysters of the same area are usually but not always pigmented. Dr. T. C. Nelson, personal communication, has observed *virginica* shells without a pigmented muscle scar and I have observed the same thing in *gigas*.

The prodissoconch characters as described by Ranson (*op. cit.*) are very interesting and biologically significant, but for the taxonomic questions of the moment they need no further discussion.

These differences tabulated in table I apply to life history, habitat, anatomy of soft parts, shape of the shell and definitive characters of the prodissoconch. It is amply clear that there are two distinct groups of edible oysters, with several species in each group, both of which deserve generic rank. As shown above, this rank has been accorded by all the leading oyster biologists who have given attention to the problem. The status of classification of the two groups under the rules of zoological nomenclature will now be discussed.

TABLE I.—A comparison of characters of Orton's type 1 and type 2 oysters. These characters are discussed in the text.

TYPE I—(exemplified by the European oyster, *Ostrea edulis*)	TYPE II—(exemplified by the common American oyster, *C. virginica*)
1. Average size smaller	Average size larger
2. Eggs retained; fertilization and larval development within mantle chamber and gills	Eggs shed free into water; fertilization and larval development take place in the water
3. Eggs large; upper limit produced at one spawning, around 1,000,000	Eggs small; upper limit produced at one spawning above 50,000,000
4. Gill ostia large	Gill ostia small
5. Have no promyal chamber	Have promyal chamber
6. Live in sea water (high salinity and clear)	Live in estuaries and brackish waters (low salinity and turbid)
7. Muscle near center of shell; muscle scar not pigmented	Muscle closer to opening between the valves; muscle scar usually pigmented
8. Lower valves flatter	Lower valves more cupped
9. Shape subcircular; more constant	Shape more elongate; more variable
10. Prodissoconch hinge long, 2 crenulations at each end; ligament at level of the cardinal plateau; valves symmetrical	Prodissoconch hinge short, 2 crenulations at each end; ligament anterior, outside the cardinal plateau; valves dissymetrical

The Genera of Living Oysters

A list of valid generic names of living Ostreidae, are given by Stenzel (1947). His interpretations were based largely on the taxonomic rules and are liberal. That some of the genera are not valid biologically and are merely synonyms will be shown. The names are:

Alectryonella Sacco 1897, p. 19
Alectryonia Fischer de Waldheim 1807
Anodontostrea Suter 1917
Crassostrea Sacco 1897, p. 15
Dendostrea Swainson 1835
Eostrea von Ihering 1907
Ostrea Linnaeus 1758
Ostreola Monterosato 1884
Saxostrea Iredale 1933
Striostrea Vialov 1936
Pycnodonte Fischer de Waldheim 1807

The genotype of *Ostrea* is *Ostrea edulis* Linnaeus, 1758. Linnaeus did not designate the type species, but it was done later by Schmidt (1818). In addition the same designation can be arrived at by absolute tautonomy, as Stenzel (1947) has pointed out in his excellent review of the status of supraspecific names of the Ostreidae. The International Commission on Zoological Nomenclature placed *Ostrea* on the Official List of Generic Names, with *edulis* as the type species, in Opinion 94 (Smithsonian Institution, 1926).

Table II gives the better known species of *Ostrea*, as restricted here, with their ranges. As Orton (1937) has pointed out, over a hundred species have been described (including both type 1 and 2 oysters), but future examination will probably show that the actual number is less.

Table II.—The better known species of type 1 oysters, Genus Ostrea as restricted here, and their ranges.

Species	Locality	Common Name
Ostrea edulis Linnaeus	Norway to Mediterranean and Aegean	European Oyster
O. cristata Born	South Atlantic and Gulf Coasts of the United States	
O. lurida Carpenter	Alaska to Baja California	Olympic Oyster
O. angasi Sowerby	South Australia and Tasmania	Mud Oyster
O. permollis Sowerby	Florida, West Indies	Sponge Oyster
O. denselamellosa Lischke	Japan	
O. stentina Payraudeau	Mediterranean	
O. puelchana d'Orbigny	Argentina	

The genus *Anodontostrea* was set up by Suter (1917) and Finlay (1928) designated *Ostrea angasi* Sowerby as the genotype. The latter species is the common Australian oyster of Orton's type 1 group (Genus *Ostrea*). Orton (1937, p. 189) says, "The Australian mud oyster, *O. angasi*, and its New

Zealand ally are so similar to the European form that one wonders whether an enterprising colonist may not some time in the past have transported samples there from Europe." He and other oyster biologists have properly ignored *Anodontostrea*, which is an unnecessary synonym of *Ostrea*, as Finlay recognized. *Eostrea* von Ihering (1907), applied to the oysters of the east coast of South America, with *O. puelchana* d'Orbigny as the type, falls in the same category. Ranson (1939) has shown that this species is larviparous and belongs to *Ostrea*.

The type of *Ostreola* Monterosato, 1884, *O. stentina* Payraudeau, is an *Ostrea* as Ranson has shown on the basis of the characters of the prodissoconch shell. I examined a shell from Naples, furnished by Dr. Myra Keen of Stanford University. The shell is that of a typical flat oyster, similar to *O. edulis*, with marginal denticles on the upper valve and opposing grooves on the lower valve near the hinge, as in *O. cristata*. The muscle scar was not pigmented and its placement indicated that no promyal chamber existed.

According to Ranson (1943) the type of *Alectryonella* Sacco, 1897, *A. plicatula* (Gmelin), is in reality a living member of the *folium-frons* group, not to be confused with *O. plicatula* of paleontologists, which is in reality a *Pycnodonte*. This then throws *Alectryonella* into synonymy with *Dendostrea* Swainson 1835, of which *O. folium* Linnaeus, was designated the genotype. But Ranson (1942) showed by the prodissoconch that *O. folium* is an *Ostrea*. Likewise he demonstrated that *O. cristagalli* Linnaeus, the type of *Alectryonia* Fischer de Waldheim 1807, is also a true *Ostrea*. The genera *Alectryonia* and *Dendostrea* have been held to be synonymous by some writers (*vide* McLean, 1941). We can accept the correctness of Ranson's views synonymizing *Alectryonella* and *Dendostrea*. If it is insisted that the shell characters of the tree oysters (prolongations of the lower valves around mangroves, corals, etc.) are definitive enough to merit generic or subgeneric separation, then *Dendostrea* is still closely allied to *Ostrea, sensu strictu*. It should be pointed out here that the prongs or lateral outgrowths of the lower shells of *Dendostrea* are absent on unattached specimens (Woodring, 1925).

There is a confused point about the tree oysters which should be cleared up. Ranson (1942) has stated that *O. folium*, the genotype of *Dendostrea* Swainson, is an *Ostrea* on the basis of its prodissoconch. However, the *folium-frons* group is often referred to as a unit and Nelson (1938) has stated that *O. frons* is an oyster with large promyal chamber and extensive aborad displacement of the muscle. This is contrary to Ranson's later findings, for all other evidence indicates that the presence and absence of the promyal chamber and the prodissoconch characters, as described by him, are correlated. McLean (*op. cit.*) states that the muscle scar of *O. frons* "is located well up towards the hinge," indicating absence of a promyal chamber. I have verified this observation on specimens in Dr. H. B. Stenzel's collection. This indicates that the species had no promyal chamber and is related to the true *Ostrea, sensu strictu*. These observations correspond with Ranson's (*op. cit.*) that the *folium-frons* group is allied to *Ostrea*. The circumstances make it appear probable that Nelson's *frons* was in reality a variant of *virginica* and not a true *frons*. Doctor Nelson has indicated in a personal communication that he now believes that was the case.

The status of *Alectryonia* is not clear. The type species is *Ostrea cristagalli*. The only shells of *cristagalli* I have seen are those in the collection of Dr. H. B. Stenzel, of the Bureau of Economic Geology of the University of Texas. The species seems to be different from the tree oysters, but provisionally we must hold in mind that *Alectryonia* and *Dendostrea* are possibly synonyms, as indicated by McLean (1941) and Ranson (1942). In that case *Alectryonia* takes precedence. Saville-Kent (1893) refers to *O. cristagalli* and *O. frons*, respectively, as the large and small coxcomb oysters. In any case Ranson (*op. cit.*) has indicated that *Alectryonia* is related to *Ostrea, sensu strictu,* which is the point pertinent to this discussion.

Ranson disregards the various shell characteristics and variations and obliterates several genera, reducing the living Ostreidae to three: *Ostrea, Gryphaea* and *Pycnodonte*. This interpretation, no matter how drastic it may seem to some conchologists, does no particular violence to the concepts of oyster biologists, who have frequently stressed the great variations in oyster shells produced by environment. Ranson's separation of *Ostrea* and *Gryphaea* on the basis of prodissoconchs corresponds with the division of species made on other grounds by Orton (1928) and Nelson (1938).

There remains the task of demonstrating the proper generic name of the type 2 oysters, which Ranson, Orton and Nelson refer to as *Gryphaea*. It is predicated that the group 2 oysters should be assigned to the genus *Gryphaea*, presumably because *Gryphaea angulata* Lamarck is considered to be the proper name of the Portuguese oyster, a member of the type 2 group. However, *Gryphaea* cannot be accepted for any living genera of oysters. Lamarck (1801) mentioned 9 species of *Gryphaea*. Three of them, including *G. angulata*, were not defined, described or indicated. Lamarck stated that he would later describe them, ". . . je caractérisai toutes celles dont je donne ici simplement le nom." The other 6 species were indicated by reference to figures in published works. Of *angulata* Lamarck merely said, "Gryphaea angulata n. Espece rarissime que l'on possède dans l'etat marin, a Paris." This certainly is not a valid description and what was meant can never be ascertained. Therefore, *angulata* of Lamarck 1801, along with *depressa* and *angustata*, are *nomina nuda*, and as such cannot under the International Rules be selected as genotypes of *Gryphaea* Lamarck Jan. 1801, regardless of whether they were later validated by proper descriptions. All of Lamarck's valid species were fossil. Anton (1839) selected *G. arcuata* Lamarck, a fossil, as the genotype. W. H. Dall (1898), Hertlein (1933) and Stenzel (1947) have all clarified this question and there is no need for it ever to rise again. McLean (1941) agreed. Lastly, the International Commission on Zoological Nomenclature has ruled in Opinion 79 (Smithsonian Institution, 1924), that "rigidly construed," Lamarck's (1801a) Systême des Animaux sans Vertèbres is not to be accepted as designations of type species.

The fossil Gryphaeas belong to the Jurassic and Cretaceous period and none should be confused with a living genus. They have a peculiar backward extension of the lower valve, recurving over the hinge and the hinge region of the upper valve, and other characteristics which clearly separate them from all other Ostreidae. They became extinct approximately 60,000,000 years ago. This is the group which some workers refer to as *Liogryphaea*. Stenzel (1947) has pointed out that in 1886 Paul Fischer made *Gryphaea arcuata* Lamarck, the genotype of *Liogryphaea*. Since *G. arcuata* was previously made the genotype of *Gryphaea* by Anton in 1839, *Liogryphaea* is an exact synonym and has no standing whatsoever as a valid name. Apparently, this erroneous usage is brought about by the misconception that Lamarck's *nomen nudum*, *Gryphaea angulata*, validated *Gryphaea* for the living genus. As was seen above, this is impossible. Therefore, *Gryphaea* applies to the Jurassic and *Cretaceous* fossils and the task of ascertaining the proper name of the living genus still confronts us.

The first valid generic name applied to the type 2 oysters is *Crassostrea* Sacco (1897), who made the American *virginica* the genotype. Hirase (1930) and McLean (1941) are the only recent workers to recognize this name, but they give it only subgeneric rank and McLean conservatively says that since we cannot assign all species to the two categories the genus *Ostrea* should be maintained for the present for all species of which the soft anatomy is not known. Certainly older names should be retained when the position of a species is in doubt, but that is no argument for subgeneric rank. The second group of oysters deserve full generic rank, as indeed it has been accorded by several workers best acquainted with oyster biology. The name of the common American oyster then is properly *Crassostrea virginica* (Gmelin). A list of the better known species of *Crassostrea* is given in table III.

TABLE III.—The better known species of type 2 oysters, Genus *Crassostrea*, and their ranges.

SPECIES	LOCALITY	COMMON NAME
Crassostrea virginica (Gmelin)	Canada to Campeche	American or Virginia Oyster
C. angulata (Lamarck)	Southern Bay of Biscay; Mediterranean	Portuguese Oyster
C. gigas (Thunberg)	Japan	Japanese Oyster
C. cucullata (Born)	East Indies	Indian Oyster
C. commercialis (Iredale and Roughley)	Australia	Rock Oyster
C. circumpicta (Pilsbry)	Japan	
C. rhizophorae (Guilding)	Cuba	Cuban Oyster

Only one subsequent name is properly a synonym of *Crassostrea*. The species *Ostrea commercialis* Iredale and Roughley was designated as the genotype of *Saxostrea* Iredale (1933). The East Indian *cucullata* is so close to the Australian *commercialis* that Orton (1937, p. 183) has indicated that possibly they are the same species. Be that as it may, *Saxostrea* differs from *Crassostrea* only in shell characteristics, which should not be considered valid grounds for separation. Orton (1937) has shown that *cucullata* is a type 2 oyster. Therefore, *Saxostrea* is a synonym of *Crassostrea*.

The status of *Striostrea* Vialov, 1936, remains to be discussed. The type species, *O. multistriata*, was described by Hanley (1846). He said, "The lower valves were attached by their entire surfaces to a ship returning from the coast of Africa." This statement is the only one relating to the type locality and it is certainly not a good one. The American oyster, *Crassostrea virginica* (Gmelin), is sometimes attached by the whole lower valve to flat surfaces and I have seen specimens striated in a manner similar to configurations of the substratum to which they were attached. McLean (*op. cit.*) has noted that *O. frons* may have a longitudinal ridge down the center of the shell, which he says is nothing more than a reflection of the gorgonium stem to which the specimen was attached. He has also noted specimens striated similarly to the *Pecten* shell to which they were attached. I have noted the same thing in *Ostrea cristata*. The species *multistriata* (if it is valid) may be a *Crassostrea*, but in any case the genus has no type locality and the description does not separate it, either from *Ostrea* or *Crassostrea*. Therefore, it remains highly doubtful.

SOME REMARKS ON THE GENERAL RELATIONSHIPS OF LIVING OYSTERS

The Pycnodontes live in pure salt water and sometimes at considerable depths. The intestine passes through the heart and the inner shell has a peculiar cellular structure, indicating that the physiological process of growth is quite different from that in other oysters (Ranson, 1939). Ranson has also shown that *Pycnodonte* differs from other oysters in having the prodissoconch hinge short, crenulated for its whole length and with the ligament outside the cardinal plateau. These points separate this well-defined group from all other oysters. Ranson (*op. cit.*) gave a list of species. *Ostrea thomasi* McLean (1941) from the east Florida coast is evidently a *Pycnodonte*. The Pycnodontes are clearly coordinate with all other living oysters.

Crassotrea is coordinate in rank with *Ostrea*. As we have seen above, Ranson relates the tree oysters *Dendostrea* (*Alectryonia, Alectryonellla, Lopha, Rastellum* of authors) to *Ostrea*. His proof of the relationship is interesting and apparently correct; but the tree oysters, in habitat, distribution, peculiar coxcomb edge of the valves, and habit of clinging to submerged stems, (with appropriate shell modifications) seem to be a well-defined tropical group, separable from *Ostrea, sensu strictu*. They may be considered coordinate or subgeneric. In any case *Crassostrea* is coordinate to the *Ostrea-Dendostrea* group.

Ranson (1942) states that *Gryphaea* (his term *Liogryphaea*) gave rise to *Exogyra* and *Crassostrea* (his term *Gryphaea*), but that the origins of *Ostrea* and *Pycnodonte* were not clear. As indicated by the above remarks, *Dendostrea* (*Alectryonia*) probably arose from *Ostrea*.

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Contribution No. 459

Samuel F. Hildebrand, Ichthyologist and Herpetologist

By Carl L. Hubbs

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Samuel F. Hildebrand, Ichthyologist and Herpetologist[1]

By Carl L. Hubbs

SAMUEL F. Hildebrand devoted his long and active career steadfastly to the advancement of ichthyology, as Leonard P. Schultz and Elmer Higgins indicate in their biographical sketches, and as the following list of his publications testifies. The only major deviation from the pursuit of this branch of science was in a series of researches on the culture and biology of turtles, that gave him rank as a herpetologist as well. It is, therefore, doubly appropriate that the American Society of Ichthyologists and Herpetologists pays tribute to him in this memorial number of Copeia.

Hildebrand's contributions to science cover a considerable range of topics, each of which represents a stage or period in his career and each of which has been significantly enlightened and advanced by his persevering labor. Mastery of each subject arose not only from innate competence, but also from his habit of concentrating on one problem at a time, with little overlap between problems, and of completing each project in turn.

In each field, Hildebrand's publications reflect his humanistic attitude as well as his scientific spirit. Much of his work either bears directly on human welfare or was designed and written for understanding and use by a large interested public, instead of by only a few specialists.

With the exception of his reports on the operation and researches of the Beaufort Laboratory, one joint study on food of trout, two obituaries of Hugh M. Smith, and the well-written chapters on "Fishes" in Tressler's *Wealth of the Seas* and in the *Smithsonian Scientific Series*, all publications by Hildebrand may be considered under eight topics:

Culture and Biology of Turtles.—The publications in this category deal largely with the artificial culture and the behavior of the valued diamond-back terrapin. Other subjects were treated and certain phases of this essentially economic research were expanded into significant contributions on growth, teratology, and hybridization.

Mosquito Control and Biology of Larvivorous Fishes.—In this field, similarly, Hildebrand produced not only technical and popular reports on the applied aspect of the investigation, but also several supplementary papers on special subjects. Particularly significant were his studies on the life-history and the sex-ratios of fishes that, largely as a result of his work, have been used very widely and successfully in the control of mosquito-borne diseases.

Early Development of Eastern North American Fishes.—Hildebrand's painstaking research and his mastery of descriptive methods are exemplified in six reports (three with Louella E. Cable) that constitute an outstanding and pioneering contribution to knowledge of the early life-history stages of American fishes. The work on the Sciaenidae was particularly thorough and important, from the standpoint of fisheries biology as well as that of natural history. Much additional material had been accumulated by Hildebrand for further needed studies in this field.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 459.

Samuel F. Hildebrand

Samuel F. Hildebrand, from a plaque by Carleton W. Angell, to be hung in the Hall of Fishes in the Museum of Zoology at the University of Michigan.

Faunal Studies on North American Fresh-water Fishes.—Seven ublications in this field (two with Barton W. Evermann) followed Hilderand's maiden contribution, a semipopular report (with Seth E. Meek) on he fishes of the Chicago area. These deal chiefly with the faunas of the Tenessee, Potomac, Catawba, Savannah and lower Mississippi rivers. They contitute a considerable though hardly an outstanding contribution.

Faunal Studies on Central American Fresh-water Fishes.—Much nore extensive and important were Hildebrand's studies in this area. *The ishes of the Fresh Waters of Panama* (with Seth E. Meek), one of his najor monographs, was, except in its initial stages, wholly the product of is own labors. It was preceded by descriptions of new species and was ather recently brought up-to-date in a supplementary catalogue. About ight other papers and notes contribute further to knowledge of the freshater fishes of Panama, Costa Rica, El Salvador and Puerto Rico.

Marine Fishes of Eastern North America.—A dozen careful studies by Hildebrand very materially advanced knowledge of the systematics, distribution, and general natural history of our East Coast fishes. The najor monograph on *The Fishes of Chesapeake Bay* (with William C. Schroeder) not only carried a large amount of new systematic and ecological data but also summarized the published information, for the benefit of the interested public as well as ichthyologists. Especially noteworthy, too, are the large reports on the systematics and biology of Tortugas fishes, which Hildebrand laboriously compiled and augmented in posthumous collaboration with William H. Longley.

Marine Fishes of Panama and Peru.—The three-volume treatise on *The Marine Fishes of Panama,* prepared by Hildebrand after the death of the nominal senior author (Seth E. Meek), and the more recent monograph, *A Descriptive Catalogue of the Shore Fishes of Peru,* will long remain standard references and are among the grandest memorials that a naturalist might desire. Both were written for general as well as specialist use. Of broad interest are his discussions of the disjunction of the tropical American marine fauna by the emergence of the Isthmus of Panama, with resultant differentiation of species, and his evidence on the partial breakdown of this barrier by the construction of the Canal. The Panamanian monograph was augmented by three short published papers and the Peruvian book has just been supplemented by a joint paper with Otis Barton. In prospect was a much-needed companion monograph on the fishes of Chile, which, along with a nearly completed general supplement to the Panamanian monograph, was unselfishly deferred, pending the completion of the manuscript on the clupeoids, for the *Fishes of the Western North Atlantic.*

Revisions of American Clupeoids and Contributions to "Fishes of the Western North Atlantic."—Hildebrand's most impressive and meritorious single contribution to systematic ichthyology was *A Review of the American Anchovies* (*Engraulidae*). Because of this accomplishment and because of his extensive studies of East Coast and Panamanian fishes, Hildebrand was assigned the sections on clupeoids for the colossal project, *Fishes of the Western North Atlantic*. To this task, in co-operative spirit, he allotted, since early in 1944, most of his time, working effectively, though handicapped by the heart ailment to which he finally succumbed. Conforming with the set policy, he recently described new species and revised the menhadens (*Brevoortia*), in preparation for the publication of the nearly completed compilations.

We trust that others will finish this task in the unselfish spirit in which Hildebrand undertook it. We also trust that his supplement to *The Marine Fishes of Panama* will be completed and published and that adequate use will be made of material accumulated for the treatise on the marine fishes of Chile and for further elucidation of the early development of Atlantic marine fishes. Ichthyologists everywhere further hope that the Fish and Wildlife Service will be wise enough to provide for the continuation and expansion of the splendid work that he was doing.

Any one of the eight series of researches discussed above would provide Hildebrand a respected place in the annals of American natural history. Together, they accord him high rank. He would be the last to claim a position among the outstandingly great and inspired leaders and would, I think, even question seriously our appraisal of him as a leading figure in the post-Jordanian period of American ichthyology. For, in addition to other fine qualities already mentioned, modesty, objectivity and self-criticism were among his outstanding traits. He was ever a steady, conscientious and intent laborer in the cause of science. All these characteristics, augmented by his genuinely co-operative and genial nature, induced warm friendship for the man, as well as respect for the scientist.

SCRIPPS INSTITUTION OF OCEANOGRAPHY (UNIVERSITY OF CALIFORNIA), LA JOLLA, CALIFORNIA.

Contribution No. 460

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Carotenoid Pigmentation of the Pomacentrid Fish *Hypsypops rubicunda*[1]

By HENRY KRITZLER,[2] DENIS L. FOX, CARL L. HUBBS and SHELDON C. CRANE [3]

DEEP-ORANGE color, due to copious quantities of xanthophyll esters of the taraxanthin class (Fox, 1936), renders the adults of the garibaldi, *Hypsypops rubicunda* (Girard), perhaps the most conspicuously brilliant fish along the rocky shores of southern California and northern Baja California. The intensity of the pigmentation raises numerous problems, bionomic as well as biochemical.

Our hearty thanks are extended to the following: The National Research Council Fellowship Board in the Natural Sciences, for the opportunity given one of us (H. K.) to spend the year of 1946-47 in residence at the Scripps Institution of Oceanography; the Rockefeller Foundation, for the support of the research program of one of us (D. L. F.) on the comparative biochemistry of marine biochromes, which program included later phases of this investigation; the Steinhart Aquarium of the California Academy of Sciences, for two specimens; Bayard H. McConnaughey and Arthur S. Lockley, for valuable assistance in several quantitative phases of the investigation; to Mr. Lockley, further, for permission to state briefly some results obtained by him in experiments on another species and for an examination of the gut contents of garibaldis; and to Jack Prodanovich and associated "Bottom Scratchers" of San Diego, for procuring needed specimens.

DEVELOPMENTAL COLOR PHASES AND THEIR BIOLOGICAL SIGNIFICANCE

Juvenile and half-grown garibaldis contrast sharply with the bright orange adults. They would, in fact, appear to be distinct species, were it not for the gradual transitions between the successive color phases. The adaptational relationships of these phases must be quite different.

At standard lengths from about 10 to 40 mm., the young, seemingly in recapitulation, rival the brilliant varicolored pomacentrids of the coral reefs (Smith, 1883). The general body color grades from pale to deep orange or scarlet, which merely sets off the spots and streaks of scintillating blue. In the upper anterior parts, back to the front part of the dorsal fin, the blue predominates. The blue is a structural color reflected from guanin platelets that allow the passage of the longer light waves, which are absorbed in the underlying sheet of melanin (Fox, 1947: 464).

The blue markings persist, but decrease in number, relative size and intensity, through the half-grown stages. Long after the blue spots on the body disappear, as the adult stage is reached, blue edgings persist on the fins, particularly along the front margin and the filament of the pelvic fin and along the outer edge of the anal.

As the blue markings become restricted at a standard length of about

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5 cm., the ground color becomes duller and browner. Except when exposed to bright light, which causes the blue spots to gleam, the half-grown garibaldi is a relatively drab fish, contrasting as strongly with the blue-spangled young as with the unicolored though brilliant adult. The dullness of the half-grown, as contrasted with the brightness of the adult, is due not only to a larger quantity of black melanin granules, masking the orange carotenoids, but also to the much lower xanthophyll content of the skin (Table I and Figs. 5–6).

TABLE I

CHANGES WITH AGE IN TOTAL SKIN XANTHOPHYLL CONTENT OF THE GARIBALDI

The values for each even 100 g. weight are taken from Figs. 5 and 6, using the line fitted by eye to the plotted determinations.

Weight of Fish, g.	Total Skin Xanthophyll, mg. per 100 g.			
	In Fish	Increment	In Skin	Increment
100	9.4	9.4	49	49
200	16.0	6.6	74	25
300	19.8	3.8	87	13
400	22.2	2.4	94	7
500	24.0	1.8	98	4

With the attainment of maturity, at a weight of about 300 g., the melanin obviously decreases and the xanthophyll definitely increases, to produce a much brighter and more orange fish.

Changes in habitat and in habits accompany the color transformations. Like the early juveniles of some other pomacentrids, the blue-spangled young at first appear to be neritic, but at a small size they take up an abode on the rocky reefs, between and just below tide limits. They live under and near ledges and about large crevices, and dart into shelter almost instantaneously when closely approached. In habitat and habits as well as in the brilliantly blue markings they seem to recapitulate the characteristics of the group as a whole. Nearly all pomacentrids are brilliant tropical reef fishes.

A somewhat similar coloration, with bright blue markings on a somewhat orange ground, characterizes the very young of the blacksmith, *Chromis punctipinnis* Cooper, the only other pomacentrid that occurs in northern Baja California and in southern California. In that species, however, the young congregate in vast mid-water swarms, as one of us (C. L. H.) has learned while diving with goggles. Furthermore, the *Chromis* rapidly transforms into a black-spotted fish, only moderately bright blue, which swims about the rocks at various depths and occasionally moves near the surface.

The dull half-grown garibaldis are quite inconspicuous, even to a "skin diver," for they slink through the crevices and vegetation of the reefs. The adults, in contrast, often leave their own crevices and display their colors over open spots on the reefs. That they have very strongly developed territorial habits has become evident from observations in aquaria as well as in nature.

The biological significance of the color must change as the garibaldis pass through their successive color phases. The juvenile color, scintillating blue on an orange to scarlet background, might be ascribed to recapitulation. But the colors are even more brilliant than those of the young of most tropical damselfishes. Neo-Darwinists will assume a positive selection for brilliance. In fact, a simple case of environmental mimicry may be involved. Occupying the range and habitat of the young garibaldis are several species of attached algae that shine with a very similar metallic blue. On the basis of specimens submitted, one of these has been identified for us by Dr. E. Yale Dawson as *Chondria californica* (Collins) Kylin; others, as species of *Rhodoglossum, Gigartina, Egregia,* and probably other genera. Some reef collectors assert that the shining blue fish actually associate with the algae of similar sheen, but we have not noticed a definite close association. Be that as it may, the environment of the young garibaldis does have splashes of metallic blue that, to human eyes at least, very closely resemble the most conspicuous element in the color of these fish. Furthermore, young garibaldis usually stay quiet, like the algae, close to the rock surface, except when they dart rapidly into crevices.

The dull brownish-orange colors of the half-grown are very inconspicuous in the retreats of the reefs that the species at this stage inhabits. Since the bright sunlight does not strike in these shadows, the remaining spots do not reflect intense blue. At this stage the fish is no doubt subject to predation and its color is obviously protective.

Due to their relatively large size, very deep body and strong fin spines, the adults must enjoy a greater immunity from predation by fish-eating birds and fishes. Their habit of remaining near their home-territory crevices and of dashing into these when alarmed, gives them much protection from larger predators, notably the California sealion, *Zalophus californianus* (Lesson). The adaptational significance of the unusual color of the adult garibaldi seems to lie in the circumstance that "the flashy orange . . . appears to advertise the presence of this fish, which boldly fights to defend its home territory" (Hubbs, 1947: 929). Its color, on this explanation, will be comparable to the color displays of birds that advertise their presence in their own defended territories.

Biochemical Studies

Many questions have arisen concerning the quantity, the chemical nature and the metabolic relations of the carotenoid pigments that render the adult garibaldi such a conspicuously orange fish. We have wished to determine: (1) age differences and individual variations (and, perhaps, geographical differences) in the xanthophyll content of garibaldis in nature; (2) the persistence or loss of integumentary xanthophyll in captivity; (3) the kinds and numbers of xanthophylls; (4) the persistence or loss of these biochromes in the skins of specimens kept on a carotenoid-free diet; and (5) whether carotene, supplied as the only type of carotenoid, might be either stored as such or converted into xanthophyll.

PROCEDURE

Accordingly, carotenoid extracts were prepared from the skins of freshly caught individuals and of specimens maintained on controlled diets. The skin alone was analyzed, because in this as in numerous other species of fish, the integument represents by far the chief permanent depot for dietary carotenoids. The underlying flesh is white.

In preparation for the analysis of their carotenoid pigments, each specimen was weighed and then killed by pithing. The skin was loosened by the immersion of the fish for 3 or 4 minutes in boiling water. The whole skin (including the white lower layers), the scales and the fins were removed, weighed and ground under initially absolute ethanol in the presence of anhydrous Na_2SO_4. Extraction of the solid material was completed in a Soxhlet apparatus with petroleum ether (b. r. 30°–60° C.). The two extracts were finally combined, and the alcohol was removed by washing with aqueous NaCl solution. The resulting orange-red petroleum ether solution was washed with distilled water, dried with pure crystalline NaCl and adjusted to a definite volume.

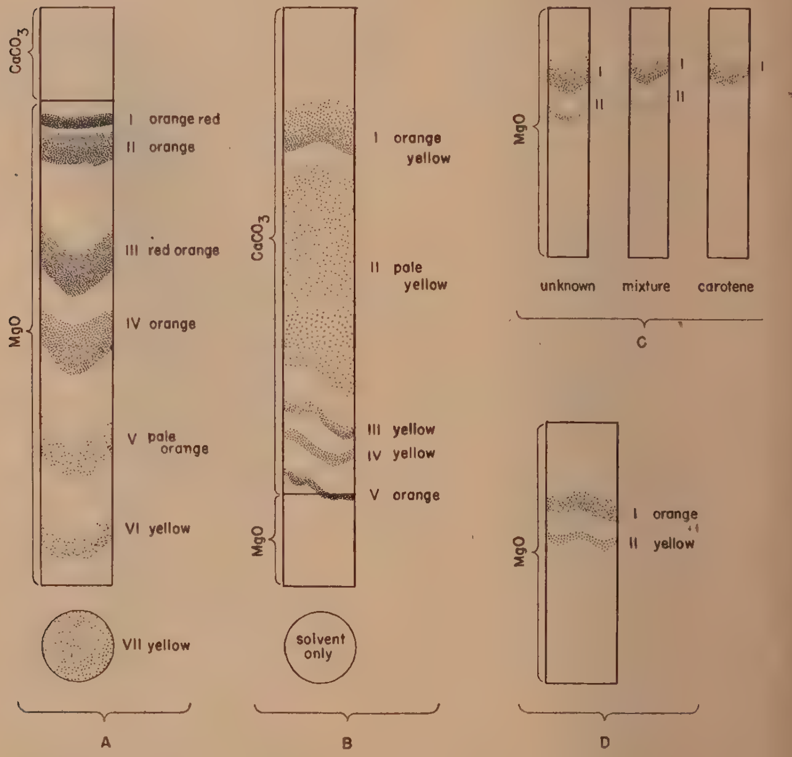

CaCO3
MgO
I orange red
II orange
III red orange
IV orange
V pale orange
VI yellow
VII yellow
A
CaCO3
MgO
I orange yellow
II pale yellow
III yellow
IV yellow
V orange
solvent only
B
MgO
I
II
I
II
I
unknown
mixture
carotene
C
MgO
I orange
II yellow
D

Fig. 1. Chromatograms obtained in fractionation of carotenoids of *Hypsypops rubicunda*.

Aliquot samples were evaporated under illuminating gas. The oily pigment residues were dissolved in CS_2. Their absorption maxima and quantities were then determined with the use of a Bausch and Lomb visual spectrophotometer. Concentrations were calculated by employing the estimated specific absorption coefficient (182.5) of violaxanthin or taraxanthin at 470μ. This estimated average value is based on numerical comparisons between absorption curves for taraxanthin (Zechmeister, 1934) in CS_2, violaxanthin in ethanol, and the specific absorption coefficients of such better known carotenoids as zeaxanthin, lutein and cryptoxanthin in CS_2 and ethanol (Strain, 1938).

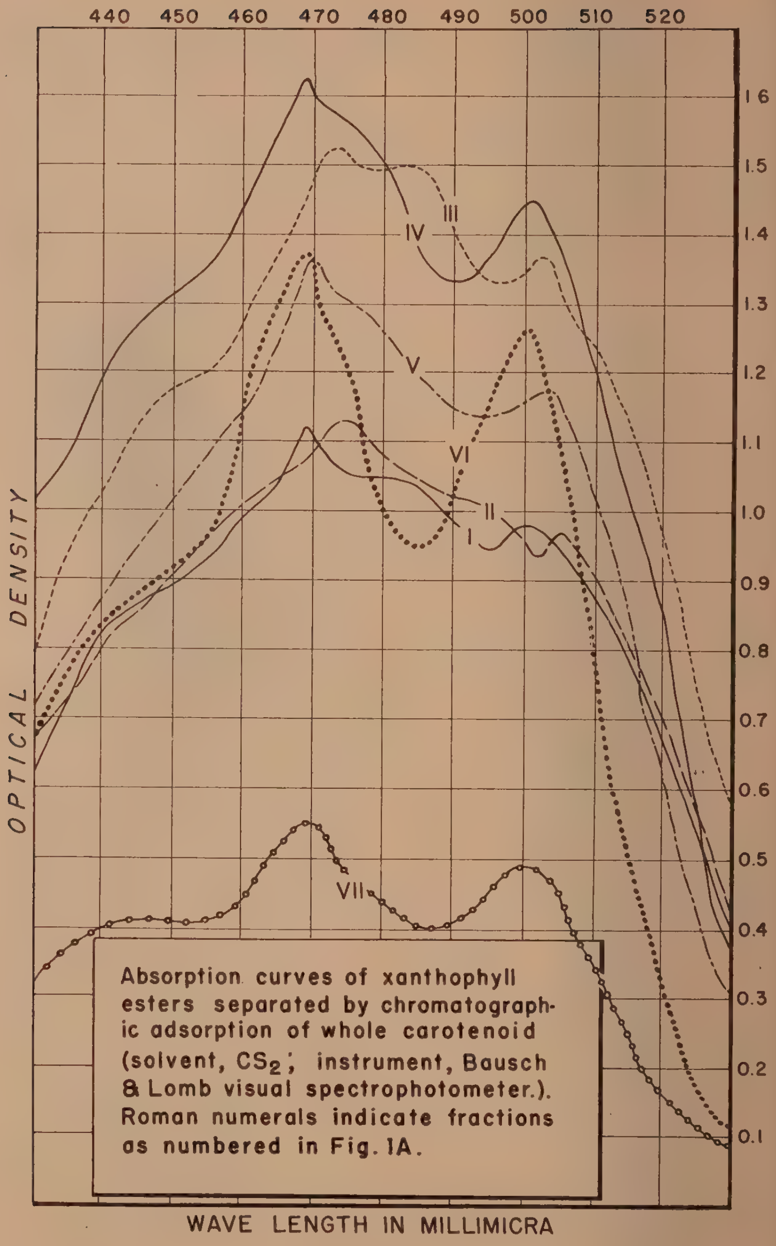
Chemical, chromatographic and spectroscopic studies were made of all extracts.

AGE, INDIVIDUAL AND GEOGRAPHICAL DIFFERENCES IN XANTHOPHYLL CONTENT

Analyses of 29 freshly caught garibaldis, all from the vicinity of La Jolla, California, and varying in weight from 64 to 515 g., prove clearly that the total xanthophyll content increases notably with age, at first very rapidly, then more slowly. Because of the wide scatter of the data, the average values, as graphed and tabulated (Figs. 5–6, Table I), are rough approximations. Refinements of data, however, cannot be expected to modify the conclusion just stated. The increase in the relative content of carotenoid pigment with age is in agreement with the observed transformation of the dull-orange half-grown fish into the brilliant orange adult.

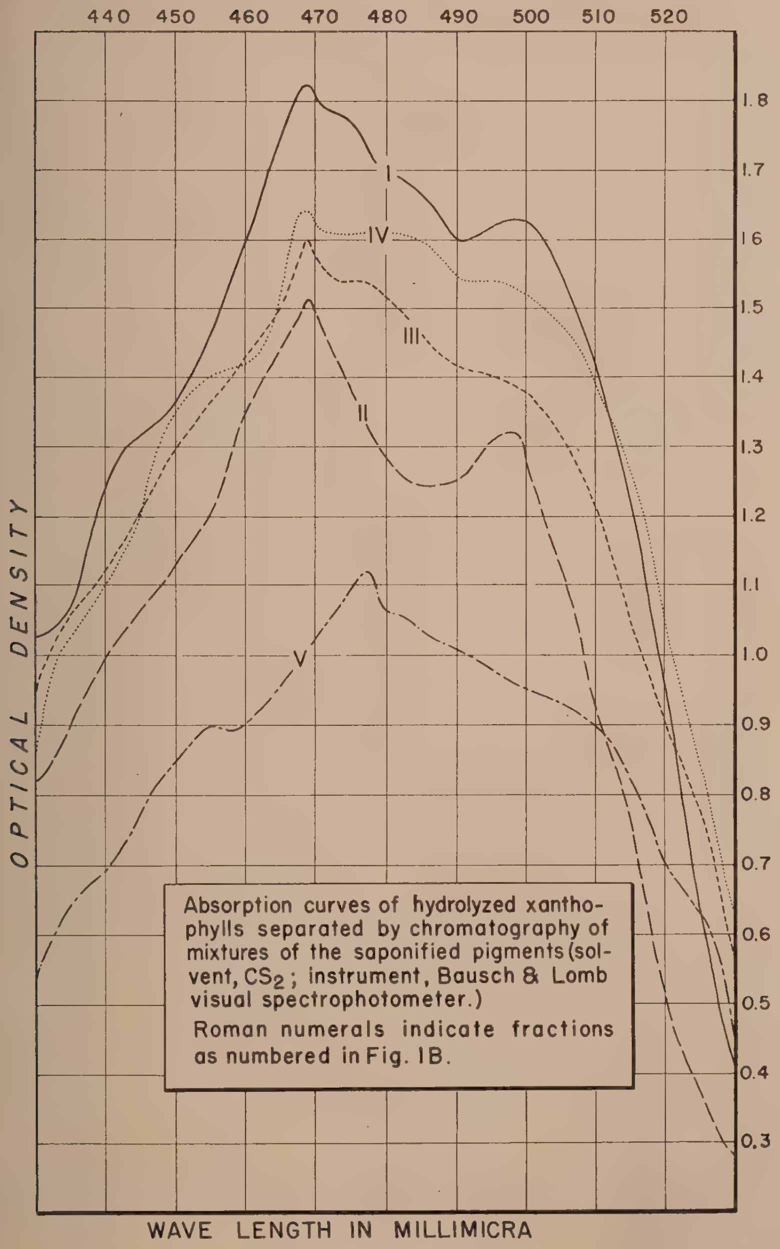
The determinations of xanthophyll content fluctuate very widely at any given size of fish. On the basis of the scatter of the data for freshly caught fish, as graphed on Figures 5 and 6, we estimate that individual fluctuations of about 50 per cent are not extremely rare. Errors in determination may be involved, but great fluctuations are also indicated by mere observation, for at any size some fish are much more orange than others.

There may also be some geographical variation in the content of carotenoid pigment, but the evidence as to temperature relationship is conflicting. When collecting fish specimens near Punta Abreojos, about half way down the coast of Baja California, where sea temperatures are definitely warmer than in southern California, one of us (C. L. H.) noted that the many garibaldis taken averaged much brighter and more orange than in California. On the other hand, adult garibaldis from La Jolla that were kept in the warm salt system (70°–75° F.) at the Steinhart Aquarium in San Francisco consistently lost their bright orange colors much more rapidly and to a greater degree than they do in the generally cooler water of the aquaria at Scripps Institution. Within a few months they became much paler and in 3 to 6 years became bleached to pale lemon-yellow. Two that had bleached out for 2 and 3 years, respectively, were sacrificed for xanthophyll analysis and their skin was found to contain only 19 and 12 per cent of the estimated average content for their respective weights (data plotted as triangles on Figs. 5–6). Several specimens caught in 1947 were placed as a trial in the cold salt system and after a year retained much more orange pigment than had those kept in the warmer water. The factors responsible for the concentration of carotenoid pigments in the skin are apparently not simple and certainly are not well understood.



Absorption curves of xanthophyll esters separated by chromatographic adsorption of whole carotenoid (solvent, CS_2; instrument, Bausch & Lomb visual spectrophotometer.). Roman numerals indicate fractions as numbered in Fig. 1A.

Fig. 2. Absorption spectra of xanthophyll esters from *Hypsypops rubicunda.*



Absorption curves of hydrolyzed xanthophylls separated by chromatography of mixtures of the saponified pigments (solvent, CS_2; instrument, Bausch & Lomb visual spectrophotometer.)

Roman numerals indicate fractions as numbered in Fig. 1B.

Fig. 3. Absorption spectra of free xanthophylls from *Hypsypops rubicunda*.

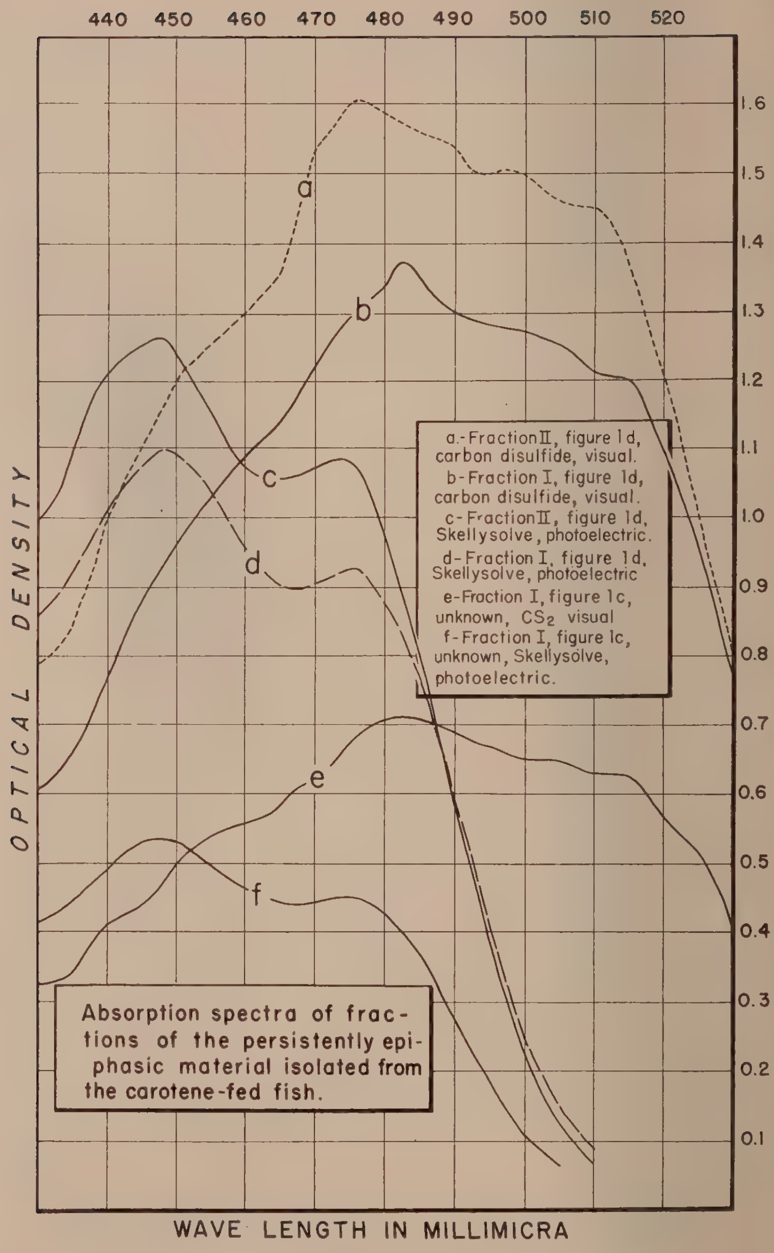


Fig. 4. Absorption spectra of fractions of the persistently epiphasic material isolated from the carotene-fed fish.

PERSISTENCE OF XANTHOPHYLL PIGMENT IN CAPTIVITY AT LA JOLLA

In the aquaria at Scripps Institution garibaldis, as noted above, do not bleach out so fast or so much as they have done on the warm salt system at the Steinhart Aquarium. In fact, good color has been retained by fish kept as long as 10 years. No analytical data have been taken from these fish.

For the interpretation of the feeding experiments it is desirable to estimate the loss of skin xanthophyll content that might be attributed to laboratory conditions. Since on the average the fish with carotene-supplemented and with carotenoid-deprived diets both ended up with a lower skin xanthophyll content than the controls (the freshly caught fish), it is possible that the loss of xanthophyll in both was due to the conditions of captivity (Table II). In the carotenoid-deprived test the 3 fish that were kept 108 to 252 days appear to have lost on the average about 5 per cent, whereas those kept 323 to 326 days seem to have lost about 28 per cent. The fluctuation is too great, however, to warrant placing much reliance on these figures.

KINDS OF CAROTENOIDS PRESENT

Portions of whole pigment extracts, subjected to partition between petroleum ether and 90 per cent methanol, proved to be epiphasic save for small traces. Samples of each phase, transferred to CS_2, exhibited the same absorption spectra (Fig. 2). Protracted hydrolysis in alcoholic KOH rendered hypophasic all of the material from fresh specimens and from those fed carotenoid-free diets (cf. Fox, 1936).

Chromatography of the whole unhydrolyzed pigment yielded 7 fractions (Figs. 1A, 2). Fraction VI was adsorbed but weakly; fraction VII, not at all. These 2 were the most alkali-resistant components. Chromatography of the individually hydrolized and subsequently recombined fractions yielded 5 elutable zones. (Figs. 1B, 3).

The altered phasic behavior of the pigment fractions following hydrolysis substantiates the earlier conclusion that the carotenoid biochromes of *Hypsypops rubicunda* are xanthophyll esters. The observation that 5 of the 7 chromatographic fractions showed absorption maxima at 469 and at 500–501 μ in CS_2 suggests that the major quantities of the material exist in nature as esters of a taraxanthin-like xanthophyll. The 2 remaining fractions (Fig. 2, II and III) of the unhydrolyzed whole pigment, which exhibit maximal absorption at about 472 and 503 μ, are similar in this respect to eloxanthin (Strain, 1938). Since they were present in relatively small quantities, their absorption characteristics were masked by those of the dominant biochrome when the spectrum of the whole pigment was examined.

The chromatographic separation from the hydrolyzed material of 4 taraxanthin-like xanthophylls may reflect either the initial presence of 4 such chemical individuals or isomerization of a single compound during chemical procedures.

The fish xanthophyll is not believed to be identical with taraxanthin. The absorption maxima of both compounds agree with those of dinoxanthin, recovered by Strain, Manning and Hardin (1944) from the fresh-water dinoflagellate *Peridinium cinctum,* as well as from the marine algal cells living commensally in the sea anemone *Cribrina xanthogrammica.*

The garibaldi xanthophyll, like dinoxanthin and taraxanthin, differs chemically from the spectroscopically indistinguishable violaxanthin (from the pansy, *Viola tricolor*) in that the latter gives an intense blue color when its ethereal solution is shaken with concentrated HCl.

No evidence was found of any qualitative changes with age in the carotenoid pigments of the garibaldi. Though analyses of the very young have not been made, it is thought that they too have the same kinds of carotenoids as do the adults.

FEEDING EXPERIMENTS

Eleven specimens were maintained at Scripps Institution in individual compartments in tanks receiving a continuous supply of fresh sea water. To avoid dietary complications, the light was held below the threshold for the development of algae, which the garibaldis would probably have eaten. Five were fed twice weekly on a diet substantially devoid of carotenoids, consisting of white "fillet of sole" (prepared from several pleuronectids), supplemented with a paste compounded of oleomargarine, $CaCO_3$, bleached wheat flour, glucose, and dried, fat-free fish meal. The diet fed to the 6 other fish differed from the foregoing only in that it included, blended with the paste, a mixture of α- and β-carotenes (1 : 9) in the equivalent of 1.0 mg. per meal per fish. The carotene-supplemented portion was fed first and was invariably consumed before hunger had abated; the remainder of the meal consisted of the control diet. The food was presented in portions small enough to be swallowed whole, one at a time, until the animals would take no more. Throughout the experiment the food was consumed with evident relish, as most of the fish became accustomed to taking the morsels at the water surface as they were offered. From the appearance of the fish it was thought that the experimental diets were adequate. All seemed to remain in good general health and activity. Their satisfactory condition was further suggested by the fact that the average ratios of skin weight to total weight for the two experimental groups (0.23 and 0.24, respectively) were only slightly higher than the average for the controls (0.22).

The differential effects of the carotene-supplemented and carotenoid-deprived diets (Table II) are difficult to evaluate quantitatively, for the following reasons: (1) the pronounced change with age in xanthophyll content (not appreciated when the experiments were run) makes comparison with a norm hazardous, particularly since the fish fed the carotene-supplemented diet were all smaller than those deprived of carotenoids; (2) the normal fluctuation of the controls also gives a dubious base line; (3) the enormous fluctuation in the analyses of the experimental animals renders comparison dubious; (4) the number of fish in each experiment was obviously too small, especially since 3 of the 5 deprived of carotenoids were kept for a shorter period than the others and may owe their lesser loss of xanthophyll to this fact (as indicated above). Since repetition of the experiment is not feasible now, however, the data are briefly summarized and discussed.

It is very probable that the fish deprived of carotenoids in their diet suffered some loss of xanthophyll from their skin. The 2 kept on this diet for 323 to 326 days were estimated to have lost respectively 15 and 41 per cent, as roughly computed by comparing the analyses of these fish with the estimated norm (Fig. 5). They may have lost more than did the larger of the fish fed the same diet with carotene added.

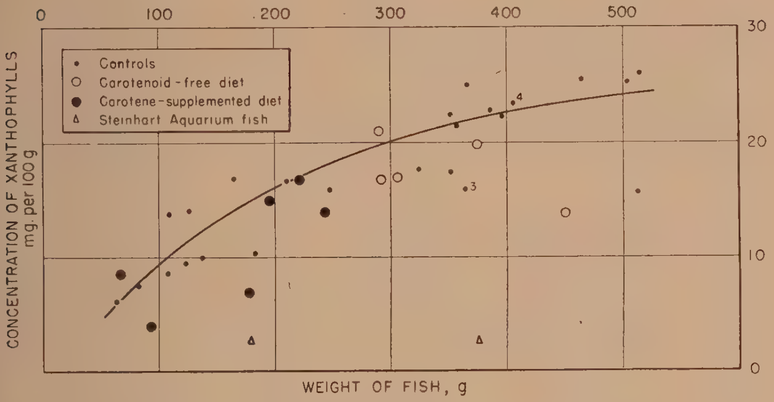


Fig. 5. Concentration of xanthophylls in mg. per 100 g. of whole fish.

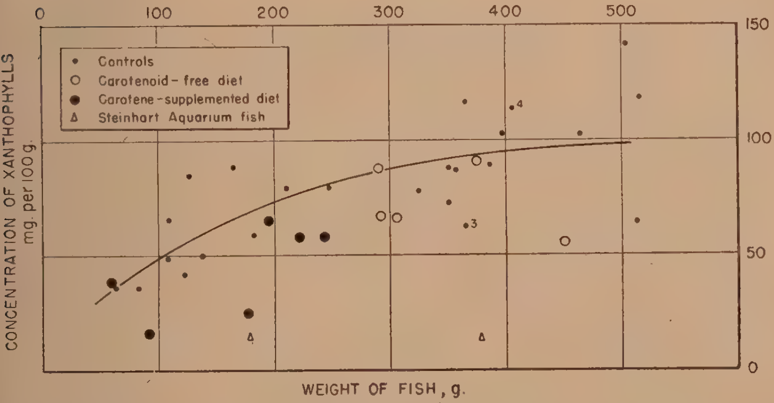


Fig. 6. Concentration of xanthophylls in mg. per 100 g. of skin. Two of the dots on Figs. 5 and 6 represent (as labelled) 3 and 4 controls, respectively, of indicated average weight.

The apparent loss of xanthophyll in the fish fed on a diet including carotene indicates that the carotene supplement did not render the animals capable of maintaining normal concentrations of skin carotenoids. More than this we may not conclude from the available quantitative data.

Some qualitative tests yield a more definite conclusion, namely, that a small part of the carotene in the diet of one group was apparently retained and deposited in the skin. The biochromes extracted from the integument of the carotenoid-deprived group did not differ qualitatively from those of the controls. Similarly, the hydrolyzable portions from the skins of the carotene-supplemented group exhibited the same series of xanthophylls. But, unlike all of the rest, the animals in this group yielded also an unhydrolyzable, persistently epiphasic fraction which proved to be β-carotene. Its identity was established by conducting the mixed chromatogram test with known β-carotene, wherein a possible artifactual isomer also appeared (Figs. 1C, 1D). Spectrophotometric measurements of the absorption maxima of this fraction, in CS_2 and in Skellysolve, confirmed its identity with β-carotene (Fig. 4 e, f).

TABLE II

CHANGES IN XANTHOPHYLL CONTENT OF SKIN UNDER DIFFERENT DIETS

Changes in the xanthophyll content are expressed as percentage deviation from the values indicated by the curve on Fig. 5, on the assumption that at the start of the experiment each fish had an average xanthophyll content. Weights were taken at close of experiment.

Days on Diet	Carotene-supplemented Diet		Carotenoid-deprived Diet	
	Weight of Fish	Change in Pigment Content (%)	Weight of Fish	Change in Pigment Content (%)
108	...	....	375	− 9
160	...	....	290	+ 8
252	...	....	292	−15
303 to 326	61	+31	...	....
	93	−56	...	....
	177	−54	...	....
	195	− 5	...	....
	222	− 1	...	....
	244	−22	...	....
	...	....	306	−15
	...	....	451	−41
Average	...	−18	...	−14*

* Average indicated loss was 5% for specimens kept 108 to 252 days; 28% for those kept 323 to 326 days.

REMARKS ON CAROTENOID METABOLISM

In its carotenoid metabolism the garibaldi exhibits some interesting contrasts with most other animals so far investigated. While consuming diets containing ample quantities of both types of carotenoid, some animals (certain birds, numerous fishes, brittle-stars, mollusks, and others) exclusively select xanthophylls, whereas others (as the horse, at least one marine worm, some sponges) select only carotenes. Certain animals, including man, frogs and octopi, assimilate all types of carotenoids from their diet. Still others, for example swine, goat, rodents, and other mammals, quantitatively reject or destroy all carotenoids. (Zechmeister, 1937; Fox, 1947; Crane, 1949.)

Several marine fishes studied in this laboratory have been observed to store no carotenes or acidogenic carotenoids, but only xanthophylls, chiefly of the taraxanthin class and only in the esterified condition. As examples, the shiner seaperch (*Cymatogaster aggregata*), the California killifish (*Fundulus parvipinnis*), and the California mudsucker, or long-jawed goby (*Gillichthys mirabilis*), are all carotene-free. When fed xanthophyll-free diets, these species have lost little or none of their skin xanthophylls during periods of several weeks. In recent experiments at Scripps Institution, by Arthur S. Lockley, *Gillichthys,* after longer maintenance on special diets, did lose some xanthophyll, but individuals on a carotene-rich diet lost less than did those deprived of carotenoids. The *Fundulus,* like *Hypsypops rubicunda,* sustains its supply of xanthophylls for periods of 90 days or more, even when fed a carotenoid-free diet (Sumner and Fox, 1935). *Fundulus* stores no dietary carotene as such, but seems able to convert it into integumentary xanthophyll. The opaleye (*Girella nigricans*) steadily loses its supply of xanthophylls when kept in laboratory aquaria (Fox, 1947). Various other fishes probably react similarly, for we have frequently noted that genera with rich yellow to red colors in nature, *Gibbonsia* for example, fade rather rapidly in captivity.

The assimilative specificity for dietary carotenoids remains an old and baffling enigma. But in *Hypsypops rubicunda* a new contingency has been revealed. For here is a species which, on a natural diet rich in both xanthophylls and carotenes, stores certain xanthophylls and quantitatively rejects carotenes (in nature, garibaldis feed chiefly but not exclusively on algae). Denied xanthophylls, but fed ample β-carotene in captivity, the fish absorbs small amounts of the carotene unchanged, while steadily losing integumentary xanthophylls. This feature of carotene assimilation presents additional complexities. A desirable extension of this study would involve the determination of whether or not the garibaldi might assimilate various xanthophylls and either store them as such or convert them into its own type of xanthophyll.

SUMMARY

The garibaldi, *Hypsypops rubicunda* (Girard), passes through 3 distinct color phases. The young are very brilliantly marked with blue on an orange to red base. In color and also in quick-hiding habits they resemble, as though by recapitulation, the damselfishes of coral reefs. The metallic blue matches that of certain algae in the same habitat. The dusky, secretive half-grown appear to be protectively colored. The adults, largely free from predation, seem to use their brilliant orange color to advertise territorial occupation.

The relative quantity of carotenoid pigments in the skin increases markedly with age, very rapidly at first, and is subject to wide individual variation. There may be some geographical variation, but evidence on relation of xanthophyll content to temperature is conflicting. Persistence of xanthophyll in captivity varies greatly.

The integumentary carotenoids of the garibaldi are chiefly esters of one or more taraxanthin-like xanthophylls, also resembling dinoxanthin, and probably not identical with taraxanthin; with a smaller fraction similar to eloxanthin. Carotenes seem to be normally lacking.

Specimens long maintained on a carotenoid-free diet apparently lost some of the integumentary xanthophylls, as did others fed on this diet supplemented with carotene. On their skin pigments the experimentally fed fish did not differ from the controls except in one significant respect: small quantities of β-carotene were stored by fish fed on a diet rich in this biochrome. This is the first demonstration of the direct assimilation and storage of carotene by a fish of normal xanthophyll-assimilating, carotene-rejecting metabolic habit.

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BACTERIAL ACTIVITIES AND THE ORIGIN OF OIL

By Dr. Claude E. ZoBell

Scripps Institution of Oceanography, University of California, La Jolla, Calif.

BACTERIA ARE responsible for the first steps in formation of petroleum from organic matter deposited in marine sediments. Extent and manner of the microbial modification of organic materials depend on environmental conditions. While bacteria play a part in the origin of oil, other mechanisms also must contribute to the process, including contact catalysts, pressure, and base exchange reactions. More research on the role played by bacteria can be expected to yield information that will be helpful to the petroleum industry in its search for new deposits. This paper is a contribution from API Research Project 43A, Scripps Institution of Oceanography, New Series No. 461. It is the summary of a lecture given before a joint meeting of the local sections of the American Institute of Chemical Engineers and the American Chemical Society in Tulsa, November 3, 1949.

INFORMATION on the origin of oil—how, when, where, and under what conditions crude oil is formed—may help the petroleum geologist in his quest for new deposits. Such information is the ultimate objective of API Research Project 43A, which has been concerned with investigating the possible part played by bacteria in the formation and modification of petroleum.[1, 2, 3]

In view of the strategic importance of oil in our mechanized and martialized civilization, it is anomalous that so little is known regarding how petroleum was formed. There are almost as many theories[4] to account for the origin of oil as there are students of the subject. No one theory seems to account for all of the facts, which suggests that oil may be formed in more than one way.[5] Most authorities[6, 7, 8, 9] agree, however, that oil has been formed from organic matter,—the remains of plants and/or animals.

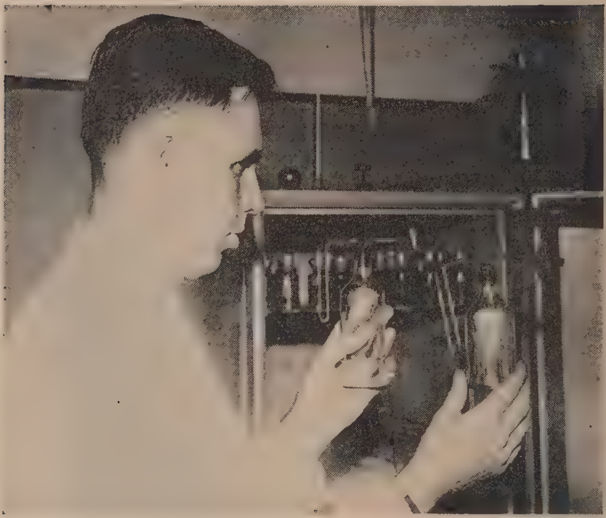
Assuming that oil had an organic origin, it is almost axiomatic that bacterial activity has contributed to the process, because virtually all types of organic compounds are susceptible to bacterial attack.

Versatility of Bacteria

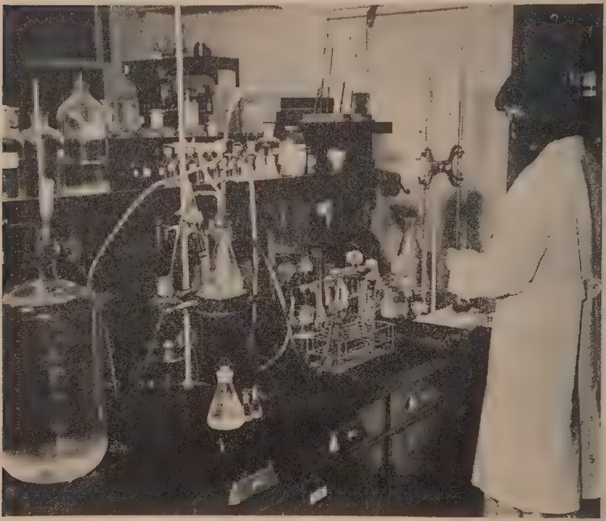
Bacteria are simple single-celled microorganisms which multiply or reproduce with extreme rapidity. Under favorable conditions, bacteria may double in number every hour or two. They occur abundantly and widely distributed in soil, sediments, and nearly every place in nature where there are moisture, minerals, and organic matter.

Some bacteria, the so-called autotrophs,[10] thrive even in the absence of organic matter. As a source of energy autotrophs may oxidize such substances as molecular hydrogen, ferrous iron, manganous manganese, hydrogen sulfide, sulfur, thiosulfates, carbon monoxide, ammonium, or nitrite. Whether bacteria which obtain their energy from the oxidation of methane and higher hydrocarbons are autotrophs or not is a matter of definition, depending upon whether the hydrocarbons are regarded as organic or inorganic.

Bacteria which require free oxygen, the aerobes, predominate in abundance, but there are a good many bacterial species, the anaerobes, which live and are physiologically active in the absence

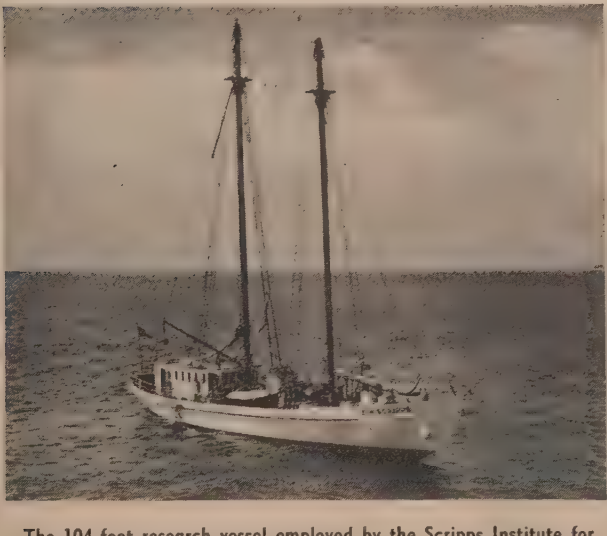


Bacteria culture bottles fitted with manometers for following gas production.



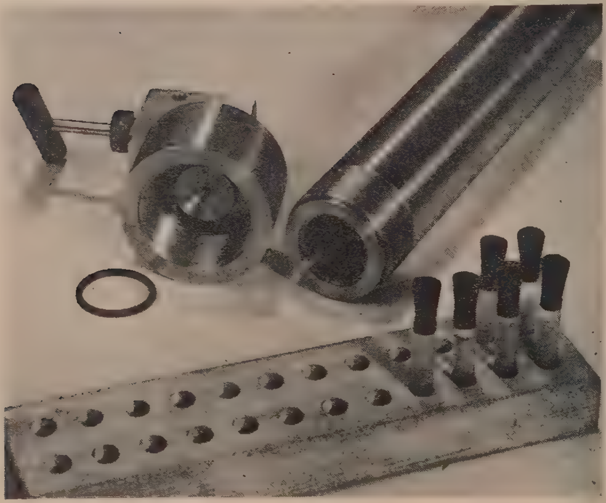
Laboratory apparatus for investigating "oil" producing bacteria.

The 1000-foot pier and principal buildings of the Scripps Institute.

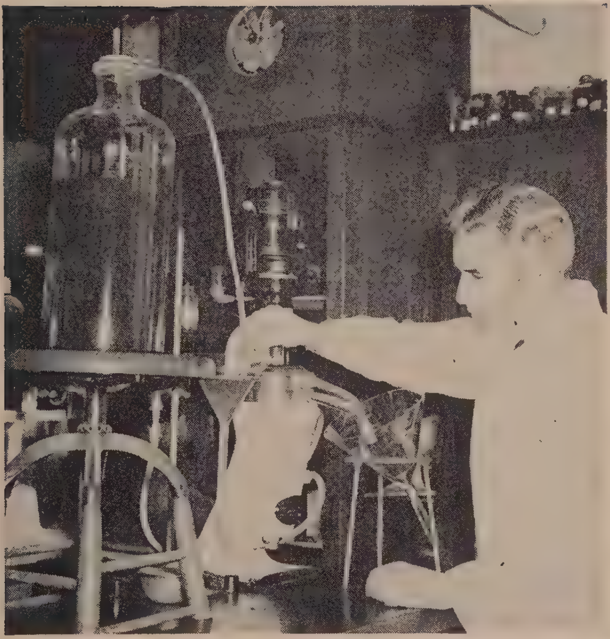


The 104-foot research vessel employed by the Scripps Institute for work at sea.

Meter and electrode assembly used for measuring the pH and redox potential of sediment samples.



The pressure cylinder sealed with an "O" ring gasket will accommodate 24 culture tubes at pressures up to 30,000 psi.



Supercentrifuge is used by Dr. W. D. Rosenfeld for separating bacterial cells from liquid in which they grow.

of atmospheric oxygen.[10] The commonest anaerobes in marine sediments are sulfate-reducing bacteria.[11] They obtain their oxygen requirements from sulfates, which are reduced to sulfur or hydrogen sulfide:

$$SO_4 + 10\,H \rightarrow 4\,H_2O + H_2S$$

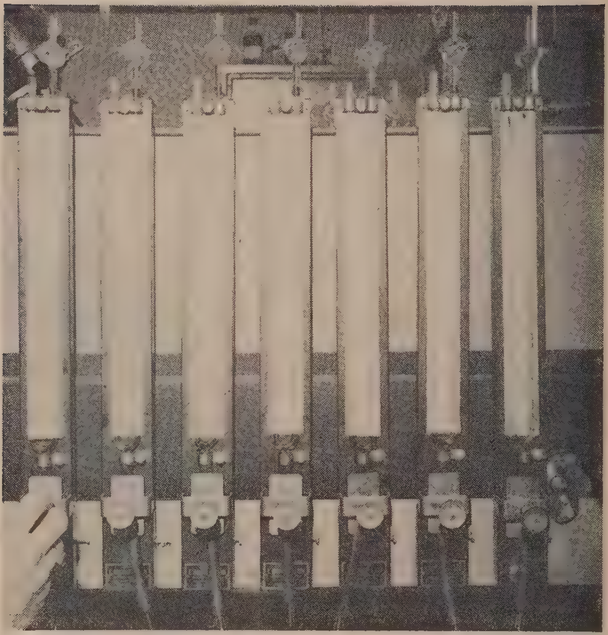
Bacteria produce a formidable array of enzymes[10] or biocatalysts which catalyze almost countless chemical reactions involving both organic and inorganic compounds. Their ability to multiply or reproduce and to produce active enzymes throughout a wide range of environmental conditions accounts for the versatility of bacteria.

There are bacteria which are biochemically active at temperatures as low as 25° F. and up to 200° F., probably higher. Some are active in the most dilute mineral salt solutions; others prefer brines saturated with salt. Some bacteria grow best at atmospheric pressure, while others thrive at hydrostatic pressures of several hundred atmospheres.[12]

From these characteristics it is apparent that bacteria could live and may be biochemically active in nearly any environment where petroleum occurs in nature irrespective of the temperature, salinity, or depth. Actually, living bacteria have been detected in petroliferous sediments and reservoir fluids from half a hundred fields and from depths of several thousand feet. Laboratory observations have demonstrated that these bacteria could be functional in such environments.[13]

Action on Organic Matter

The organic remains of plants and animals may be modified by bacterial activity in various ways, depending primarily upon the environmental conditions and the kinds of microorganisms



A battery of micro-respirometers employed for following the amounts of gases produced or consumed by bacteria.

present. In surface soil, as in well oxygenated water, the general tendency is for organic matter to be oxidized or mineralized, the end products being largely water, carbon dioxide, ammonia, sulfate, and phosphate. Under other environmental conditions bacteria tend to bring about the humification of organic matter, a process in which humus[14] and other complex organic residues result.

Under still other environmental conditions, bacteria and allied microorganisms, assisted by other agencies, catalyze the carbonization or coalification of organic matter, as in peat bogs[15] where there is a progressive decrease in the hydrogen, oxygen, nitrogen, sulfur, and phosphorous content of organic matter. A similar process, with one noteworthy exception, tends to convert organic matter into oil. In the latter process, which can be designated reduction or hydrogenation, there is also a decrease in the oxygen, nitrogen, sulfur, and phosphorous content of organic residues, but instead of the hydrogen to carbon (H/C) ratio decreasing, as in the coalification process, the tendency is for the H/C ratio to increase.

The reduction or hydrogenation of organic residues results in the formation of substances which are more petroleum-like in composition. This may be illustrated by the following data on the chemical composition of organic residues recovered from the sea floor and of crude oils from different fields:

Element	Organic Residues	Crude Oils
Carbon	45.4-56.0 percent	82.2-87.1 percent
Hydrogen	5.1- 8.9 percent	11.7-14.7 percent
Oxygen	24.3-33.6 percent	0.1- 4.9 percent
Nitrogen	9.7-15.7 percent	0.1- 1.5 percent

It will be observed that whereas they contain a higher percentage of hydrogen than most marine organic residues, crude oils contain considerably less oxygen and nitrogen.

When subjected to the action of anaerobic bacteria under highly reducing conditions in the laboratory, the organic remains of marine plants and animals are slowly decomposed with the liberation of carbon dioxide, ammonia, hydrogen sulfide, etc. Although the total carbon content may diminish during this process, the resulting residue is relatively richer in both carbon and hydrogen as it contains a decreasing percentage of oxygen, nitrogen, and sulfur.

A similar change in the chemical composition of the organic matter found in certain marine sediments of increasing antiquity (period or depth of burial) has been observed. Thus, laboratory as well as field observations indicate that under certain conditions, bacteria tend to convert organic matter into residues which are more petroleum-like in character. Fractions of the residues have been shown to consist of liquid and solid hydrocarbons which are indistinguishable from petroleum hydrocarbons.

Bacteria Produce Hydrocarbons

That methane, a common constituent of natural gas and crude oil, is produced by bacteria has been known for several decades. Methane is formed[16] during the anaerobic fermentation of organic matter and possibly by other bacterial processes under environmental conditions resembling those in which petroleum is found and in which petroleum is believed to have been formed. There is also evidence for the bacterial formation of minute traces of ethane, propane, and certain other gaseous hydrocarbons, but certainly not in the concentrations in which these hydrocarbons occur in natural gases associated with crude.

A good many bacterial species[10] produce carotene, leprotene, rhodopurpurin, flavorhodin, and other complex pigmented hydrocarbons having the empirical formula $C_{40}H_{54-58}$. Although such hydrocarbons are not constituents of petroleum, they illustrate the ability of bacteria to synthesize complex hydrocarbons.

Certain sulfate-reducing bacteria, isolated from marine sediments, produce small amounts of liquid and solid hydrocarbons while utilizing fatty acids. Such hydrocarbons are synthesized as part of the bacterial cell substance, probably in much the same way as the rubber tree or the guayule plant synthesizes hydrocarbons.

Although the yields are small, it is significant that bacteria do produce liquid and solid hydrocarbons resembling those found in crude oil. The best yields from fatty acids to date have been of the order of from 0.01 to 0.05 percent of the carbon appearing as liquid and solid hydrocarbons. Whether other types of bacteria or other experimental conditions may yield higher concentrations of petroleum hydrocarbons are unexplored possibilities.

During the decomposition of proteins, bacteria produce phenol and para-cresol,[17] two compounds which occur quite commonly in crude.

Transformation of Hydrogen

Since the conversion of organic matter into petroleum hydrocarbons is a process which involves hydrogenation reactions, it is noteworthy that some bacteria liberate hydrogen from organic compounds and others catalyze the utilization of hydrogen.[18] Three different physiological types of anaerobic bacteria, which utilize hydrogen and thereby may be instrumental in the origin of oil, have been investigated.

One type catalyzes the combination of molecular hydrogen with organic compounds. Unsaturated compounds such as linolenic and linoleic acids and hexadecene, for example, are hydrogenated by these bacteria in accordance with the following reaction:

$$RCH = CHR + H_2 \rightarrow RCH_2CH_2R$$

where R is an alkyl group such as—CH_3, —C_2H_5, —C_3H_7, etc., or some other radical. Such bacteria also catalyze the reductive deamination of amino acids by molecular hydrogen:

$$RCHNH_2COOH + H_2 \rightarrow RCH_2COOH + NH_3$$

Both processes, it will be observed, tend to convert certain kinds of organic compounds into products which are more petroleum-like. The direct decarboxylation of the compound, RCH_2COOH, would result in the formation of a hydrocarbon. Acetic acid is decarboxylated by certain bacteria with the liberation of methane:

$$CH_3COOH \rightarrow CO_2 + CH_4$$

Whether higher fatty acids are decarboxylated by bacteria with the formation of higher hydrocarbons is still problematical. Bacteria catalyze the decarboxylation of amino acids:

$$RCHNH_2COOH \rightarrow CO_2 + RCH_2NH_2$$

A second type of hydrogen-utilizing anaerobe catalyzes the reduction of carbon dioxide (or carbonates) with the formation of methane:

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

A third type of hydrogen-utilizing anaerobe brings about the reduction of sulfates:

$$H_2SO_4 + 4\,H_2 \rightarrow H_2S + 4\,H_2O$$

By itself this reaction may not be of direct importance in the origin of oil except that it may help to account for the reduction of sulfates, a process which seems to have occurred rather commonly in brines associated with petroleum deposits. Of greater importance may be the multiplication or growth of bacteria which obtain their energy from the foregoing reaction. Upon chemical analysis the cell substance of these bacteria, which utilize hydrogen as the sole source of energy, is found to contain appreciable quantities of oily material.[19] The carbon comes from carbon dioxide or carbonates.

Hydrogen[18] for these reactions in source sediments of petroleum may come (a) from the bacterial fermentation or organic compounds, (b) from the interaction of certain inorganic compounds such as ferrous sulfide and hydrogen sulfide, for example, or (c) from the alpha-radiation of compounds containing hydrogen.

In view of the rather general presence in petroliferous sediments of radioactive constituents which tend to liberate hydrogen, hydrogen-utilizing bacteria[18] may assume significance as agents which help to account for the general paucity of free hydrogen in such environments.

Effect of Bacteria on Redox Potential

Bacteria growing in marine sediments devoid of free oxygen tend to create conditions which are more and more reducing in intensity. In other words, the tendency is for bacteria to lower the redox potential of sediments containing organic matter. The redox potential is the degree of oxidation or reduction of a reversible oxidation-reduction system, or it is a measure of how reducing or how oxidizing the system is with respect to some standard.

Marine sediments rich in organic matter and having a high bacterial population generally have a low redox potential.[20] It becomes lower with the age of the material or with core depth. The reducing conditions or low redox potentials of marine sediments are attributed to the activities of bacteria which consume oxygen, organic compounds, and other oxidizing substances. Once created, the reducing conditions are maintained by ferrous iron, manganous manganese, hydrogen sulfide, and certain reducing bacterial products.

Low redox potentials retard the oxidation of organic matter and promote hydrogenation reactions. By creating low redox potentials bacteria favor the formation as well as the preservation of petroleum hydrocarbons.

Liberation of Oil

There are several ways[21] in which bacteria may liberate oil from oil-bearing materials and promote its flow or accumulation in reservoirs. One of the most obvious ways is by the destruction of organic matrix containing oil. A second way is by dissolving sulfate or carbonate rocks to which oil is adsorbed. With the dissolution of such rocks or sediments, the adherent oil is free to flow and at the same time void spaces, pores, or channels may be formed or enlarged, thereby favoring the movement or accumulation of oil.

Third, carbon dioxide produced by bacteria tends to decrease the viscosity of oil and thereby promotes its movement. This may be said also of methane. Carbon dioxide, methane, hydrogen, and other gases produced by bacteria in micro-traps or capillary cavities may help to expel oil therefrom.

Fourth, certain bacteria which grow on solid surfaces crowd oil off from such surfaces. Especially effective are surface-dwelling bacteria which produce surface-tension depressants or detergents.

All four mechanisms whereby bacteria liberate oil from oil-bearing materials have been demonstrated by laboratory experiments.[21] Such bacterial processes may have contributed significantly to the migration and accumulation of oil throughout the geological ages. Whether it will prove to be practical to apply any or all of these bacterial processes to the secondary recovery of oil is a question which can be answered only by further investigations.

Microbial Modification of Oil

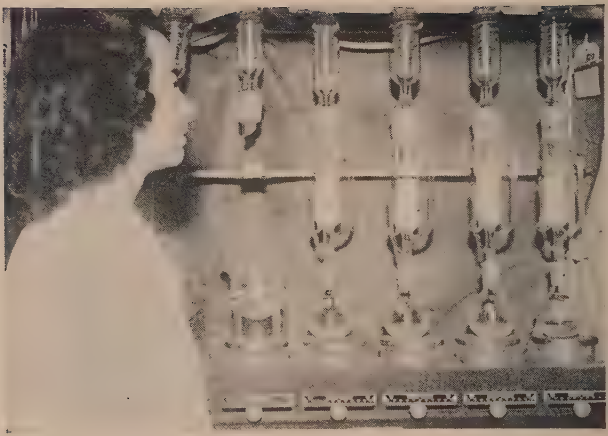
In the presence of mineral salts solutions virtually all kinds of petroleum hydrocarbons are attacked by bacteria or allied microorganisms.[22] This generalization is based upon work with more than a hundred pure hydrocarbons ranging in complexity from methane to dibenzanthracene as well as work with numerous mixtures of hydrocarbons. These mixtures include natural gases, ligroins, petroleum ethers, gasolines, benzines, distillates, fuel oils, lubricating oils, paraffin waxes, tars, asphalts, asphaltenes, coal tars, and samples of crude oil from many fields.

Bacteria, actinomyces, molds, and yeasts, which attack petroleum hydrocarbons, appear to be quite widely distributed in nature. They are especially abundant[22] in bottom waters over which petroleum products are stored, in oil-well brines, in cooling or cutting oils containing water, and in oil-soaked soil around swamps, oil pumps, refinery effluents, etc. Although most oil-oxidizing microorganisms require free oxygen, a few species utilize petroleum hydrocarbons in the absence of atmospheric oxygen. Anaerobic sulfate-reducing bacteria are in this latter category.

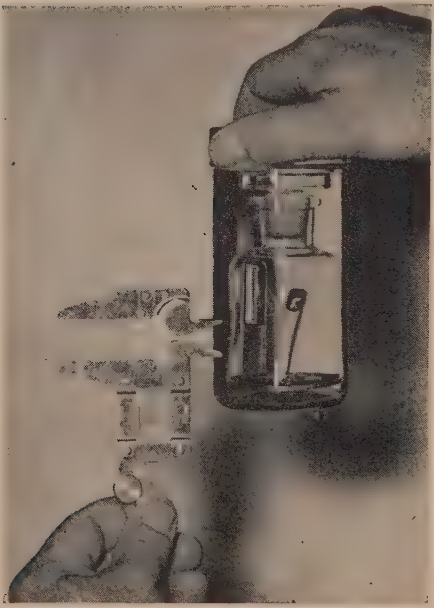
The activities of oil-oxidizing bacteria may account for the absence of oil from certain areas where it appears to have been present. Quite possibly oil accumulates only in environments where conditions are not conducive to the activities of such bacteria. This possibility suggests the desirability of learning much more regarding the factors which influence the activities of oil-oxidizing bacteria, because by so doing we may discover significant characteristics of source beds of petroleum which may prove to be useful in the search for new oil fields.

Investigations on the abundance or activities of methane-oxidizing bacteria in surface soil, as in so-called geomicrobiological prospecting procedures, may be one step in this direction.

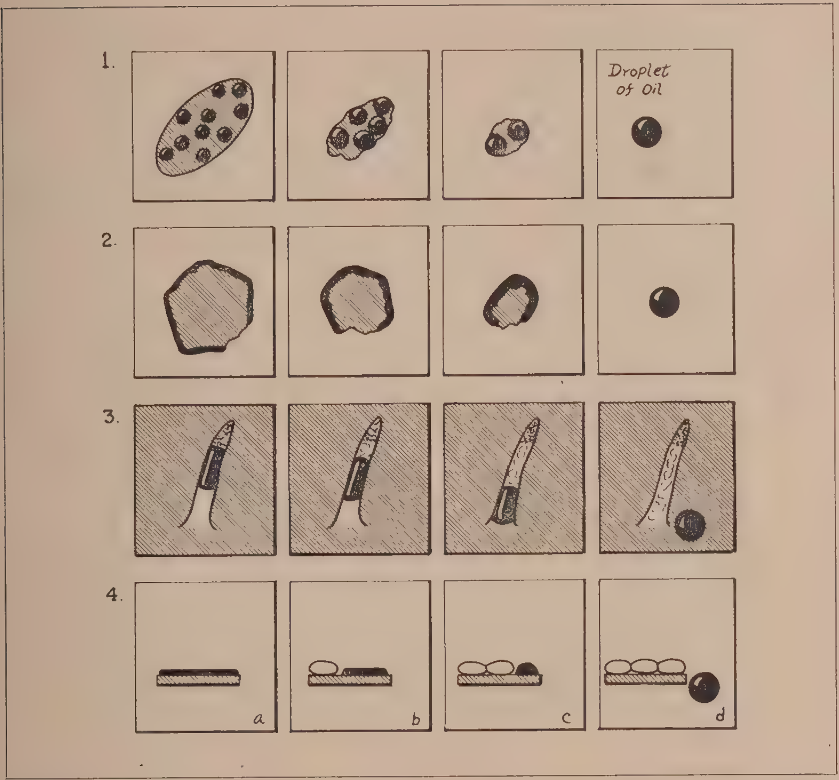
The ability of oil-oxidizing bacteria to affect crude and petroleum products in laboratory experiments suggests that such bacteria may have played a part in the modification of petroleum or its constituents. Certain bacteria, for example, which selectively attack unsaturated compounds may help to account for the general lack of olefinic hydrocarbons in crude oils. The selective action of other types of bacteria on ali-



Soxhlet extraction apparatus used for extracting ether-soluble substances from bacteria or their products.



Double water-jacketed apparatus for following hydrogen utilization by bacteria.

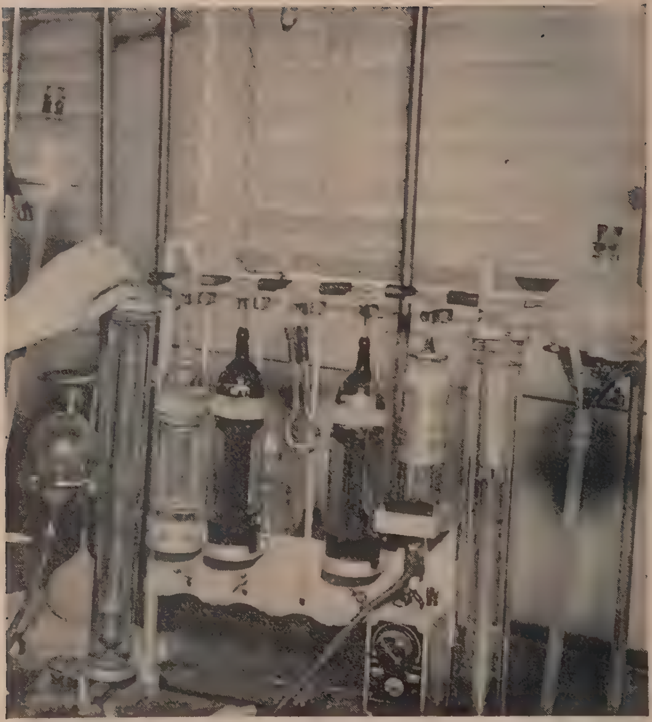


Diagrammatic representation of the principal ways in which bacteria release oil from oil-bearing materials and promote its accumulation, stages of action being depicted from left to right: 1. Micro-droplets of oil are liberated and coalesce as organic matrix is decomposed. 2. Gradual dissolution of carbonate (or sulfate) particle results in liberation and accumulation of adherent oil. 3. Gases produced in micro-trap expel oil. 4. A micro-film of oil on solid surface is displaced by bacteria which grow on such surfaces.

phatic or paraffinic hydrocarbons may help to explain why some deposits are predominantly naphthenic in character. On the other hand certain bacteria tend to attack preferentially naphthenic compounds and large molecules.

Both increases and decreases in the gravity of oil samples have been observed to be caused by bacterial action. The extent and direction of the change in the properties of crude oil caused by bacteria seems to be a function of the types of bacteria present, the environmental conditions, and the kinds of compounds present in the crude.

The sulfur, nitrogen, and oxygen content of petroleum may be largely due to bacterial activities in source sediments of petroleum. A decrease in the nitrogen and sulfur content of crude oil samples has been observed, but under other experimental conditions oil-oxidizing bacteria have caused increases in the sulfur and oxygen content of oils.



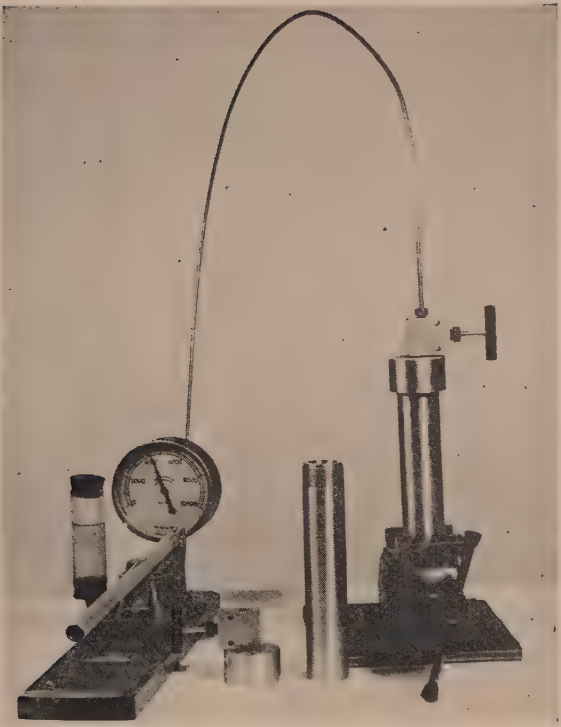
Modified Orsat gas analysis used for determining amounts of hydrogen, carbon dioxide, methane, and oxygen in gas mixtures modified by bacteria.

While there are several ways in which bacteria may modify crude oil in sediments, the facts are too fragmentary to warrant any conclusions or generalizations other than those suggested by preliminary observations.

Summary and Conclusions

Bacteria and allied microorganisms are responsible for the first steps in the formation of petroleum from organic matter deposited in marine sediments. This conclusion is inescapable because the organic remains of all plants and animals are susceptible to attack by bacteria or their enzymes. The extent and manner of the microbial modification of organic materials depend primarily upon environmental conditions.

In sediments lacking free oxygen the general tendency is for anaerobic bacteria to convert organic matter into substances which are more and more petroleum-like in chemical composition by deaminations, decarboxylations, methylations, desulfurizations, and other processes. Methane as well as liquid and solid hydrocarbons are produced in small amounts by bacteria which utilize organic compounds. Petroleum hydrocarbons are also produced from carbon dioxide or carbonates by autotrophic bacteria which oxidize molecular hydrogen as the sole source of energy. The microbial utilization of molecular hydro-



Hydraulic hand pump for applying pressures to bacterial cultures in steel cylinder up to 10,000 psi.

gen may account for its general absence in natural gases from sediments.

Bacterial activities in sediments may favor the formation and preservation of petroleum hydrocarbons by lowering the redox potential. Bacteria may also contribute to the migration and accumulation of oil by liberating oil from oil-bearing materials.

During and after its formation oil may be modified in various ways by bacteria which attack hydrocarbons and other constituents of petroleum.

While bacteria play a part in the origin of oil, there is no reason to postulate their mutual exclusiveness because contact catalysts, pressure, base exchange reactions, and other mechanisms must contribute to the process also. Much more research work will be required in order to appraise accurately the role played by bacteria. Such research can be expected to yield information that will prove to be useful to petroleum people in their search for new deposits.

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ON THE WIND-DRIVEN OCEAN CIRCULATION

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(Manuscript received 24 September 1949)

ABSTRACT

Streamlines of oceanic mass transport are derived from solutions to a vertically integrated vorticity equation which relates planetary vorticity, lateral stress curl, and the curl of the stress exerted by the winds on the sea surface. These solutions account for many of the gross features of the general ocean circulation, and some of its details, on the basis of the observed mean annual winds.

The solution for *zonal winds* (section 3) gives the main gyres of the ocean circulation. The northern and southern boundaries of these gyres are the west wind drift, the equatorial currents, and equatorial countercurrent. They are determined by the westerly winds, the trades, and the doldrums, respectively. For each gyre the solution gives the following observed features (from west to east): a concentrated current (*e.g.*, the Gulf Stream), a countercurrent, boundary vortices (the Sargasso Sea), and a steady compensating drift. Using mean Atlantic zonal winds, the solution yields a transport for the Gulf Stream of 36 million metric tons per second, compared to 74 million as derived from oceanographic observations. The discrepancy can probably be ascribed, at least in part, to an underestimate of the wind stress at low wind speeds (Beaufort 4 and less) as derived from the relationship now generally accepted.

The solution for *meridional winds* (section 5) accounts for the main features of the current system off California. For a *circular wind system* (section 8) the solution gives a *wind-spun* vortex which is displaced westward in relation to the wind system, in agreement with observations in the Northeast Pacific high-pressure area.

Based on these three solutions, a general nomenclature of ocean currents is introduced (section 9), applicable to all oceans regardless of hemisphere, and suggestive of the meteorologic features to which the currents are so closely related. In the light of this general system, the circulations of the northern and southern hemispheres, and of the North Atlantic and North Pacific are compared (section 10). Rossby's jet-stream theory of the Gulf Stream, and Maury's theory of thermohaline circulation are discussed, and it is concluded that the circulation in the upper layers of the oceans are the result chiefly of the stresses exerted by the winds.

roduction

s study is a resumption of Ekman's (1923; 1932) ive effort to account theoretically for the main es in the general ocean circulation. The tempta- reopen this problem is provided by three recent pments: (*a*) Rossby's (1936) introduction of stresses associated with the horizontal exchange e eddies; (*b*) Sverdrup's (1947) computation of uatorial countercurrents in a baroclinic ocean he known wind stress; and (*c*) Stommel's (1948) ation of the westward intensification of a wind- d circulation in terms of the variation of the is parameter with latitude.

kman's and Stommel's model the ocean is as- homogeneous, a case in which the currents ex- the very bottom. Not only is this in contrast bservations, according to which the bulk of the transport in the main ocean currents takes place upper thousand meters, but it also leads to matical complications which rendered Ekman's analysis very difficult, and forced Stommel to resort to a rather arbitrary frictional force along the bottom.

To avoid these difficulties, we retain Sverdrup's integrated mass transport as the dependent variable. This device makes it possible to examine the more general case of a baroclinic ocean without having to specify the nature of the vertical distributions of density and current. In recognition of the evidence that currents essentially vanish at great depths, we shall depend on lateral friction for the dissipative forces. From Stommel we retain the rectangular boundaries, although we extend the basin to both sides of the equator and deal with the *observed* wind distribution rather than a simple sinusoidal distribution.

2. The differential equation of mass transport

Let the x-axis point eastward along the equator, the y-axis northward, and the z-axis vertically upwards from a level surface (assumed plane) just beneath the sea surface (unit vectors **i**, **j**, **k**). For the present, the nonlinear inertial terms are considered negligible, an assumption which will be examined in section 10. The equations of steady horizontal motion for a unit volume are

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[1] tribution from the Scripps Institution of Oceanography, ries, No. 462. This paper was prepared partly under a heim Fellowship at the University of Oslo, partly with the of the Office of Naval Research.

$$\nabla_H p + f\mathbf{k} \times (\rho \mathbf{v}_H) - \frac{\partial}{\partial x}\left(A'_H \frac{\partial \mathbf{v}_H}{\partial x}\right) - \frac{\partial}{\partial y}\left(A'_H \frac{\partial \mathbf{v}_H}{\partial y}\right) - \frac{\partial}{\partial z}\left(A'_V \frac{\partial \mathbf{v}_H}{\partial z}\right) = 0, \quad (1)$$

where $\nabla_H = \mathbf{i}\,\partial/\partial x + \mathbf{j}\,\partial/\partial y$, p is pressure, ρ is density, $\mathbf{v}_H = \mathbf{i}\,v_x + \mathbf{j}\,v_y$ is the two-dimensional (horizontal) velocity vector, and $f = 2\omega \sin \varphi$ is twice the vertical component at latitude φ of the earth's angular velocity ω. Observations have shown that A'_V, the dynamic eddy viscosity associated with vertical shear, is different from A'_H, the eddy viscosity pertaining to horizontal shear, the two coefficients bearing a ratio rather larger than that of the width of the ocean currents to their depth. We shall assume A'_H horizontally isotropic, neglecting variations that might be related to differences between zonal and meridional motions of of large horizontal eddies on a rotating earth.

The equations of motion will be integrated from some constant depth, $-h$, beneath which the motion and horizontal pressure gradients essentially vanish (Sverdrup, 1947), to the surface, $z = z_0(x, y)$. Let

$$P = \int_{-h}^{z_0} p\, dz, \qquad \mathbf{M}_H = \int_{-h}^{z_0} \rho\, \mathbf{v}_H\, dz, \quad (2a, b)$$

designate the integrated pressure and mass transport. Then

$$\int_{-h}^{z_0} \nabla_H p\, dz = \nabla_H P - p_{z_0} \nabla_H z_0,$$

where p_{z_0} is the atmospheric pressure and $\nabla_H z_0$ is the gradient of the sea surface. The second term is negligible for the present investigation.

The integration of the horizontal shearing forces is more cumbersome. The simplest form is $A_H \nabla^2_H \mathbf{M}$, where A_H is an effective kinematic eddy viscosity which is assumed independent of x and y. There is no evidence to indicate that the complicated expression given by a complete integral with a variable $A_H = A'_H/\rho$ would be a more accurate description of the forces. Finally

$$\int_{-h}^{z_0} \frac{\partial}{\partial z}\left(A'_V \frac{\partial \mathbf{v}_H}{\partial z}\right) dz = \left[A'_V \frac{\partial \mathbf{v}_H}{\partial z}\right]_{z_0} - \left[A'_V \frac{\partial \mathbf{v}_H}{\partial z}\right]_{-h} = \boldsymbol{\tau}, \quad (3)$$

where $\boldsymbol{\tau}$ is the stress applied by the wind on the sea surface. In most ocean areas it is adequate to select a depth h of 1000–2000 meters, which is comfortably above the sea bottom. The foregoing equation could be used even where the current extends to the bottom, provided $\boldsymbol{\tau}$ would then designate surface stress minus bottom stress.

With the understanding that all operators and vectors have only horizontal components, the subscript H can be dropped, and the integrated equations of m tion become

$$\nabla P + f\mathbf{k} \times \mathbf{M} - \boldsymbol{\tau} - A\, \nabla^2 \mathbf{M} = 0. \qquad (4$$

The vertical integration enables us, therefore, to avo any assumptions regarding the variation of A'_V wi depth, and to postpone an examination of the densi and velocity structure in depth.

The surface kinematic boundary condition requir w_{z_0} to vanish for steady state; furthermore it has be assumed that $w_{-h} = 0$. Therefore $\nabla \cdot \mathbf{M} = 0$, $M_x = -\,\partial\psi/\partial y$, $M_y = \partial\psi/\partial x$, *i.e.*,

$$\mathbf{M} = \mathbf{k} \times \nabla\psi, \qquad ($$

where ψ is the mass-transport stream function (dime sions: mass/time). Substituting ψ into (4) and perfor ing the curl operation to eliminate P gives the diff ential equation of mass transport

$$\boxed{(A\nabla^4 - \beta\, \partial/\partial x)\psi = -\,\mathrm{curl}_z\, \boldsymbol{\tau},} \qquad ($$

where $\mathrm{curl}_z\, \boldsymbol{\tau}$ is the vertical component of the wi stress curl, $\nabla^4 = \partial^4/\partial x^4 + 2\,\partial^4/\partial x^2 \partial y^2 + \partial^4/\partial y^4$ is t biharmonic operator, and $\beta = df/dy$ is the rate change northward of twice the vertical component the earth's angular velocity.

Equation (6) is an integrated version of the vortic equation. Ekman calls $\beta\, \partial\psi/\partial x = \beta M_y$ the planet vorticity. Accordingly, the vorticity equation (6) presses a balance between lateral stress curl, planet vorticity and wind-stress curl.

For boundary conditions we choose

$$\psi_{\mathrm{bdry}} = 0, \qquad (\partial\psi/\partial\nu)_{\mathrm{bdry}} = 0, \qquad (7a,$$

where ν is normal to the boundary. The first equat states that the boundary itself is a streamline (wh value is arbitrarily selected as zero); the second eq tion states that no slippage takes place against boundary.

The problem is to solve (6) subject to bound conditions (7). Hidaka (1949) has given the for solution employing the transformation into a va tional problem. There is a remarkable analogy betw this problem and a problem arising in the theory elasticity (Rayleigh, 1893; Love, 1944, p. 464). deflection ψ of a plate of uniform flexural rigidity clamped at its boundaries and subjected to a l $-\mathrm{curl}_z\, \boldsymbol{\tau}$ is governed by

$$A\nabla^4\psi = -\,\mathrm{curl}_z\, \boldsymbol{\tau},$$

subject to boundary conditions (7). Equation (6) duces to this form when the planetary vorticit negligible, a condition that might arise in high tudes ($\beta \approx 0$) and for quasizonal flow ($M_y \approx 0$). analogy suggests experimental methods for fin streamlines under complex wind stress and bound conditions.

Solution for zonal winds

rectangular ocean is assumed, extending from $= 0$ to $x = r$, and from $y = -s$ to $y = +s$. One y think that such an arbitrary choice of ocean indaries would make it impossible to deal with ual conditions. Yet the proper solution for the *in features* in the ocean circulation can be expected be rather insensitive to the choice of boundaries, ause these main features are similar in all oceans ble 3) although the boundaries are not. The bound- conditions (7) become

$$= 0, \qquad \partial\psi/\partial x = 0, \qquad \text{for } x = 0, \quad x = r; \qquad (9)$$

$$= 0, \qquad \partial\psi/\partial y = 0, \qquad \text{for } y = -s, y = s. \qquad (10)$$

or a *zonal* wind circulation ($\tau_y = 0$) the stress on sea surface in the interval $-s < y < +s$ can written as a sum of terms like

$$\tau_{zn} = a \cos ny + b \sin ny + c$$

ere $n = j\pi/s$, $j = 1, 2, \cdots$ *etc.* The vertical com- ent of the wind-stress curl is then a sum of terms

$$\mathrm{l}_{zn}\, \tau = -\partial\tau_{zn}/\partial y = n(a \sin ny - b \cos ny), \qquad (11)$$

the particular integral of (6) becomes

$$= -n^{-3}A^{-1}(a \sin ny - b \cos ny)$$
$$= -n^{-4}A^{-1}\,\mathrm{curl}_{zn}\,\tau. \qquad (12)$$

$k = \sqrt[3]{\beta/A}$ designate the *Coriolis-friction* wave nber, assumed constant. The solution to the homo- eous equation

$$(\nabla^4 - k^3\, \partial/\partial x)\psi_{hn} = 0, \qquad (13)$$

be written as a product of $(a \sin ny - b \cos ny)$ a function of x. For later convenience we choose form

$$\psi_{hn} = \psi_{pn}(rAn^4\beta^{-1}X_n - 1), \qquad (14)$$

ere X is a function of x to be determined below. complete integral equals

$$\psi_n = \psi_{pn} + \psi_{hn} = rAn^4X_n\beta^{-1}\psi_{pn},$$

$$\psi_n = -rX_n\beta^{-1}\,\mathrm{curl}_{zn}\,\tau. \qquad (15)$$

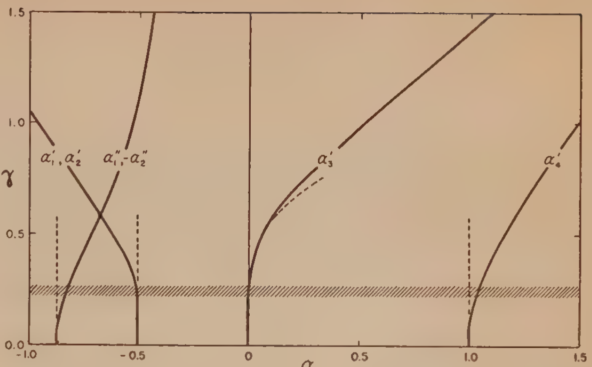

FIG. 1. Roots $\alpha' + i\alpha''$ to characteristic equation (16). The dashed lines give the asymptotic solutions for $\gamma \ll 1$ which have been applied to the large scale features ($\gamma < 0.25$) in the ocean circulation.

It follows from (12), (13) and (14) that the function $X_n(x)$ must obey the differential equation

$$X'''' - 2n^2X'' - k^3X' + n^4X = \beta/rA = k^3/r,$$

which yields

$$(\gamma_n{}^4kr)X = 1 + \tfrac{1}{2}(p_1 + ip_2)e^{\alpha_1kx} + \tfrac{1}{2}(p_1 - ip_2)e^{\alpha_2kx} + p_3e^{\alpha_3kx} + p_4e^{\alpha_4kx},$$

where $\gamma = n/k$ is the essential nondimensional number in this investigation, and where $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are the roots of the characteristic equation

$$(\alpha^2 - \gamma_n{}^2)^2 = \alpha. \qquad (16)$$

This equation has two complex roots, $\alpha_1' + i\alpha_1''$, $\alpha_2' + i\alpha_2''$, and two real roots, α_3', α_4' (fig. 1). For small values of γ,

$$\alpha_1 = -\tfrac{1}{2}(1 + i\sqrt{3}), \qquad \alpha_3 = \gamma_n{}^4,$$
$$\alpha_2 = -\tfrac{1}{2}(1 - i\sqrt{3}), \qquad \alpha_4 = 1, \qquad (17)$$

as shown by the dotted lines in fig. 1. The boundary conditions (9) give

$$-p_1 \approx -p_2\sqrt{3} \approx 1 + p_3 \approx p_4 \approx \gamma_n{}^4kr, \qquad (18)$$

provided

$$\gamma_n{}^4 \ll 1, \qquad e^{-kr} \ll 1, \qquad e^{-\gamma_n{}^4kr} \approx 1 - \gamma_n{}^4kr. \qquad (19)$$

Subject to these approximations,

$$X = -Ke^{-\frac{1}{2}kx}\cos\left(\frac{\sqrt{3}}{2}kx + \frac{\sqrt{3}}{2kr} - \frac{\pi}{6}\right) + 1 - \frac{1}{kr}[kx - e^{-k(r-x)} - 1] \qquad (20)$$

$$\underbrace{\frac{X'}{k} = Ke^{-\frac{1}{2}kx}\sin\left(\frac{\sqrt{3}}{2}kx + \frac{\sqrt{3}}{2kr}\right)}_{\text{west}} \qquad \underbrace{\underbrace{-\frac{1}{kr}[1 - e^{-k(r-x)}]}_{\text{central}}}_{\text{east}}, \qquad (21)$$

ere $K = 2/\sqrt{3} - \sqrt{3}/kr$. The meaning of the hori- tal braces will be discussed later.

he important thing to notice is that, to the present degree of approximation, X does not depend on n; *i.e.*, that the response of the current to the zonal wind stress is without distortion in the y-direction for

$\gamma \ll 1$. Equation (15) can therefore be written

$$\boxed{\psi = -rX\beta^{-1}\,\mathrm{curl}_z\,\boldsymbol{\tau},} \tag{22}$$

and the stream function computed directly from the observed (zonal) stress without expanding the stress in a Fourier series, provided such a series converges so rapidly that for all significant terms conditions (19) are fulfilled. Whether this is the case can usually be told by inspection. Anticipating the numerical values $k = .016\ \mathrm{km}^{-1}$, $r = 6000$ km, conditions (19) for 10 per cent accuracy in ψ give $\gamma < 0.25$, corresponding to a minimum zonal wave length $2\pi/n$ of about 1500 km. For the mean annual stress distribution (fig. 2) the shortest wave length of the important N-S variations is the distance between the northern and southern trades, 4000 km. *The approximations leading up to (22) appear to be valid for a study of the general ocean circulation as it is related to the general atmospheric circulation.*

For stationary compact cyclones and sharp fronts with *overtones* of less than 1500 km wave length ($\gamma > 0.25$), it is necessary to compute separately the components ψ_n for each component wind stress $\boldsymbol{\tau}_n$ according to equation (15), and to sum. The roots α can be read off fig. 1 and the p's determined by the original boundary conditions (9).

There remain the conditions (10) at the norther and southern boundaries. We note (fig. 9) that th winds are weak at 60°–70° latitudes, and we sha satisfy (10) by assuming $\mathrm{curl}_z\,\boldsymbol{\tau}$ and its derivative approach zero at these boundaries. It must be a mitted that this easy way of satisfying boundary co ditions is aided by the present lack of adequate wi data in high latitudes.

To the extent to which these conditions on curl_z are not satisfied there must be deviations from th present solution, but we may expect these deviatio to be restricted to relatively narrow zones adjace to the northern and southern boundaries for the fo lowing reasons: The general circulations in the A lantic and Pacific Oceans are in a very rough sen symmetrical with respect to the equator (except for a asymmetry related to the asymmetry of the wind ci culation), whereas the boundaries are not. To th south all oceans open into the Antarctic Sea, to th north they are practically closed. Even the India Ocean, with its northern boundary only 1000–20 km north of the equator, has about the same circul tion in its central and southern parts as the Atlant and Pacific.

It is none the less possible that important featur have escaped us by the present incomplete treatmen

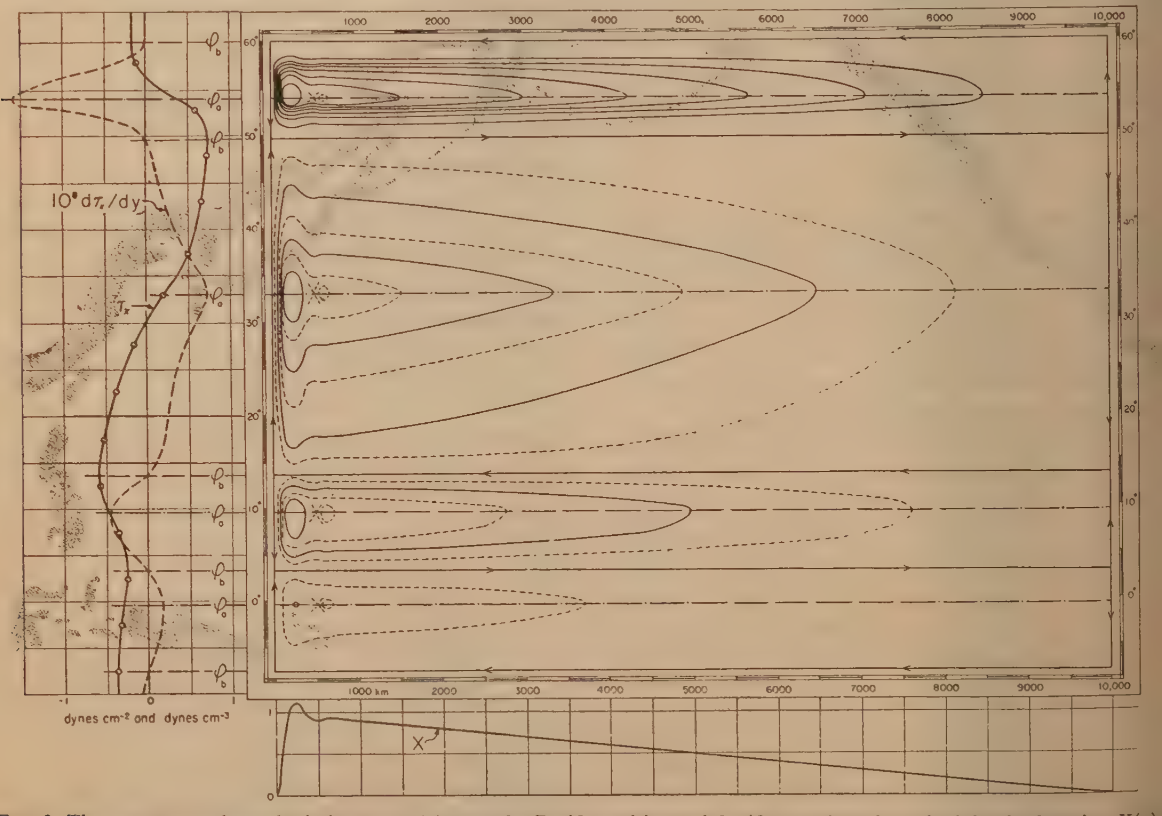

FIG. 2. The mean annual zonal wind stress $\tau_x(y)$ over the Pacific and its curl $d\tau_x/dy$ are plotted on the left, the function $X(x)$ the lower part. These functions have been combined graphically according to equation (22) to give mass transport streamlines $\psi(x,$ The transport between adjacent solid lines is 10×10^{12} g sec^{-1}, or 10 million metric tons sec^{-1}. The total transport between the co and any point x, y is $\psi(x, y)$. The chart of the Pacific has a uniform distance scale throughout. In the relatively narrow northern p tion, the transport is greatly exaggerated.

d we hope to be able to give a complete numerical
ution (for actual boundaries) at a later time. The
nilar but much simpler problem of a rectangular
te clamped at its edges and subject to a uniform
d (equations 8, 9, 10 with curl$_z$ $\boldsymbol{\tau}$ constant) has
eived considerable attention, yet no complete theo-
ical solution has been found, and recourse has had
be made to rather elaborate numerical methods
ove, 1944, pp. 493–497). We note, however, that the
ution in the vicinity of the transverse axis (corre-
onding to low and middle latitudes) for a plate which
more than twice as long as broad is practically the
ne as if the length were infinite.

Zonal wind currents

The wind stress has been computed for the North
cific and the North and Central Atlantic for each
nth and 5-degree quadrangle. The source material
nsisted of the wind roses on the U. S. Hydrographic
ice Pilot Charts of the North Pacific Ocean, the
nmary of Marine Data Cards of the U. S. Weather
reau, and the Monthly Meteorological Charts of
Atlantic Ocean prepared by the Meteorological
ice, Air Ministry, London. The variability of the
nd and the hydrodynamic character of the sea sur-
e has been taken into account in the manner de-
ibed by Reid (1948). Fig. 2 shows the mass trans-
rt streamlines $\psi(x, y)$ in a rectangular ocean com-
ted from (22) for the mean annual *zonal* winds over
Pacific. The topography of the free surface and of
er isobaric surfaces is related to the ψ-topography,
relationship depending however on the vertical
nsity structure. For the equatorial Pacific, Reid
48b) has successfully used a simple model of ver-
al density distribution consisting of a homogeneous
er of density ρ_0 and thickness h' above an *exponen-*
l layer of density $\rho_{-\infty} - (\rho_{-\infty} - \rho_0) \exp(1 + z/h')$.
He finds

$$P + \mathit{constant} = \tfrac{5}{8} g \frac{\rho_0{}^2}{\rho_{-\infty} - \rho_0} z_0{}^2$$
$$= (5/2) g (\rho_{-\infty} - \rho_0) h'^2 \approx f\psi \quad (23)$$

for the elevation z_0 of the surface above, and the depression of h' beneath their mean level.

The major ocean gyres.—The zonal wind system divides the ocean circulation into a number of gyres, each bounded by latitudes φ_b for which $M_y = 0$, or by (22),

$$\text{curl}_z\, \boldsymbol{\tau} = 0 \text{ at } \varphi = \varphi_b.$$

The major dividing lines between gyres correspond to the latitudes of maximum west winds, of the northerly and southerly trades, and of the doldrums (fig. 2). These compare favorably with those determined from oceanographic observations.

The latitudinal *axis* of each gyre may be defined by $M_x = 0$, or

$$\frac{d}{dy} \frac{\text{curl}_z\, \boldsymbol{\tau}}{\beta} = 0 \approx \frac{d^2 \tau_x}{dy^2} \qquad \text{at} \qquad \varphi = \varphi_a.$$

The Atlantic Sargasso Sea is associated with the inflection point in the mean wind stress curve between the westerly winds and the northeasterly trades.[2] The inflection points between the doldrums and the northern and southern trades determine the boundaries of the equatorial countercurrent.

The western currents.—Along any fixed latitude, ψ varies with X only, and the curves $X(x)$ and $X'(x)$ in fig. 3 can be interpreted as the north–south component of transport, and transport per unit length, drawn to an arbitrary scale. For definiteness, consider sections at latitudes φ_a through the center of gyres.

When X and X' are computed from (20) and (21), it is found that the equations fall naturally into three parts, each of which dominates in a given sector. At

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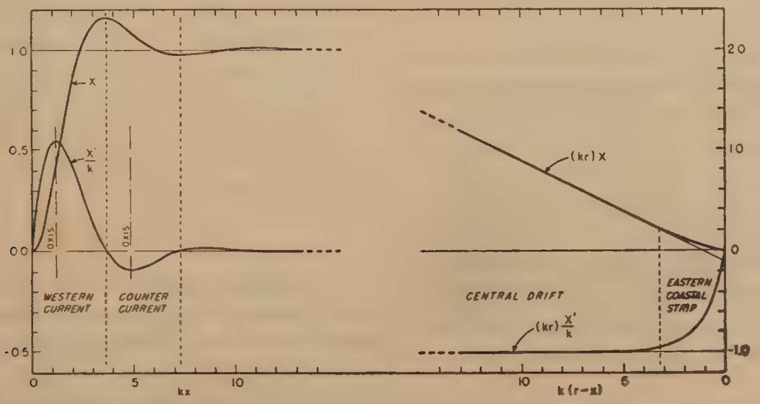
[2] The dependence $r(y)$ of the width of the ocean basin on latitude somewhat modifies this conclusion when applied to nonrectangular ocean basins (Munk and Carrier, 1950).



IG. 3. Plot of equations (20) and (21), giving the west–east variation in transport ($\sim X$) and transport velocity ($\sim X'$) from the
stern shore ($x = 0$) to the eastern shore ($r - x = 0$). The scale for the central and eastern solutions is exaggerated relative to the
le for the western solution.

the western edge of the ocean $x \ll r$, and

$$X_{\mathrm{W}} = -\frac{2}{\sqrt{3}} e^{-\frac{1}{2}kx} \cos\left(\frac{\sqrt{3}}{2}kx - \frac{\pi}{6}\right) + 1, \qquad (20\mathrm{W})$$

$$\frac{X'_{\mathrm{W}}}{k} = \frac{2}{\sqrt{3}} e^{-\frac{1}{2}kx} \sin\frac{\sqrt{3}}{2}kx, \qquad (21\mathrm{W})$$

representing slightly *underdamped* oscillations of wave length

$$L_{\mathrm{W}} = \frac{4\pi}{\sqrt{3}k} = \frac{4\pi}{\sqrt{3}\sqrt[3]{\beta}} A^{\frac{1}{3}}. \qquad (24)$$

TABLE 1. Extrema of X_{W} and X'_{W}.

	Location (see fig. 3)			
	Western current axis	Western current limit	Counter-current axis	Counter-current limit
x/L_{W}	1/6	3/6	4/6	1
X_{W}	0.45	1.17	1.09	0.97
X'_{W}/k	0.55	0.00	−0.09	0.00

Table 1 gives the locations and values of the first few extrema. A remarkable feature is a countercurrent east[3] of the main current, whose magnitude is $\exp(-\pi/\sqrt{3})$, or 17 per cent of that of the main current. There can be little doubt that such countercurrents exist, although this fact has been obscured in some instances by the smoothing of data. In comparing the Kuroshio and the Gulf Stream, Wüst (1936, p. 56) remarks that (writer's translation) ". . . both currents are accompanied by a countercurrent on their right which attains surface velocities up to approximately 20 cm sec⁻¹. This current, which is found for all Gulf Stream profiles based on *Atlantis* and *Dana* observations is a most peculiar phenomenon." According to Wüst's figures, the maximum speeds of the countercurrents average 19 per cent of that of the main currents, compared to the theoretical value of 17 per cent. In describing the Gulf Stream, Iselin (1936, p. 43) states that ". . . the western margin of the current is extremely abrupt, while on the eastern side the velocity decreases gradually." The theory places the current axis twice as near the western as the eastern side.

The function X_{W} (fig. 3) compares favorably with the transport function ψ (fig. 4) across the Gulf Stream and Kuroshio computed from oceanographic data according to the equations

$$\frac{f\psi}{\bar{p}} = Q = \int_{-h}^{z_0}\int_{-h}^{p(z)} \delta'\,dp\,dz, \qquad (25)$$

where δ' is the specific volume anomaly (Sverdrup *et al.*, 1942, p. 463), although there remain significant differences between the computed and observed transport curves, and of course between the observed currents themselves.

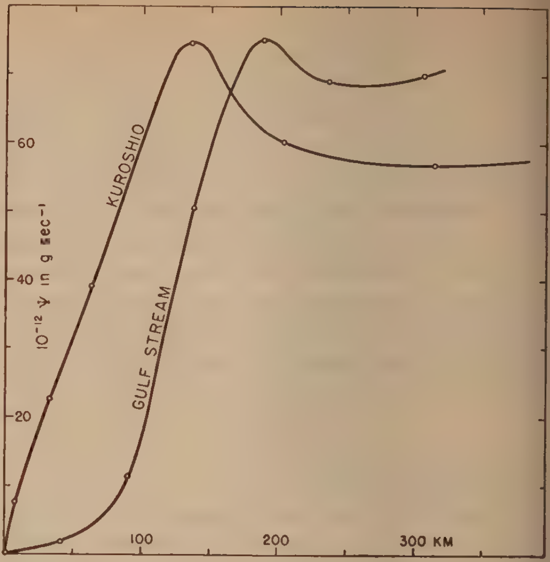


FIG. 4. The mass transport stream function ψ computed fro oceanographic data across the Kuroshio and Gulf Stream. The curves should be compared to the theoretical function X on tl left side of fig. 3. GULF STREAM: *Atlantis* stations 1225–123 April 1932 (Iselin, 1936); $x = 0$ is placed at boundary betwe coastal water and slope water. KUROSHIO: *Mansyu* stations 42 434, January 1927 (Wüst, 1936); $x = 0$ is placed at continent shelf.

A review of oceanographic observations suggests 20 km and 250 km as typical values for the widths of th western currents and countercurrents, respectivel The corresponding values of A are 3.3×10^7 an 6.5×10^7 cm² sec⁻¹ (equation 24), indicating perhap an increase of A with distance from shore as might b expected on the basis of Prandtl's mixing-lengt theory. We shall set $A = 5 \times 10^7$ cm² sec⁻¹. Th compares favorably with the values 4×10^7 an 7×10^7 cm² sec⁻¹ for the region of the Atlantic equa torial countercurrent, the former determined by Mont gomery (1939) from the diffusion of salt, the latter b Montgomery and Palmén (1940) from dynamic prin ciples. One may expect, however, that the value of varies with time and location, and that for any fixe time and location it has different values, depending o the dimensions of the phenomenon under investiga tion. Without any further information we shall b obliged to consider the above value as constant.

The *total* transports of the western current an countercurrent are found by substituting values fo X_{W} from table 1 into (22):

$$\psi_{\mathrm{WC}} = -1.17 r\beta^{-1}\,\mathrm{curl}_z\,\tau. \qquad (26$$

The resulting expressions *are independent of A*, an the transports can be computed with a relatively hig degree of accuracy, being subject largely to uncertain ties of the same order as those in computing win stress. A comparison is made in table 2 between th transport values of some western currents determine from oceanographic observations, and those compute

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[3] A countercurrent on the *western* edge of the Gulf Stream has been accounted for by Rossby (1936) in his wake-stream theory. Further remarks will be found in section 10.

TABLE 2. The mass transport of some western currents determined from the wind stress (equation 26) and from oceanographic observations.

Current	Lat.	$10^{13}\beta$ cm^{-1} sec^{-1}	r km	$10^{10}\frac{d\tau_x}{dy}$ g sec^{-2}	Merid. wind factor	$10^{12}\psi$ Wind stress g sec^{-1}	$10^{12}\psi$ Oceanogr. g sec^{-1}
Stream	35°N	1.9	6,500	70	1.30	36	74^4 $(55)^5$
oshio Ext.	35°N	1.9	10,000	50	1.25	39	65^4
shio C.	50°N	1.5	5,500	−15	—	−6.5	-7^6
il C.	20°S	2.2	5,500	−20	—	−5.8	-5 to -10^4

Sverdrup *et al.* (1942), pp. 605–761.
djusted for a supposed southward motion of 19 × 10^{12} g of slope water per second. Sverdrup *et al.* (1942), p. 679.
or August (Uda, 1938).

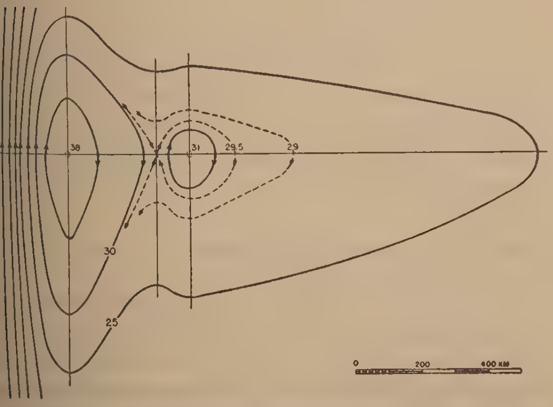
n the zonal wind stress according to (26). The effect he meridional wind component, which supports the al winds, is introduced by a meridional wind factor section 7)

$$-\overline{\text{curl}_z\,\boldsymbol{\tau}}\,(d\bar{\tau}_x/dy)^{-1}. \qquad (27)$$

approximation involved in permitting the "con- nts" β and r to assume different values at different tudes implies that these vary slowly compared to nd ψ. However, not even a rapid change of r intro- es an appreciable error into (26); the only essential dification is a widening and corresponding weaken- of the western current, determined by the inclina- of the western coastline relative to the assumed th–south direction (Munk and Carrier, 1950).

he computed transport values differ from the ob- ved values by as much as a factor of two, a dis- pancy not surprising if one considers that, among er uncertainties, wind and current data are not for same year, nor necessarily for the same time of r. On examining the possible sources of errors, one ed to ascribe some of the discrepancy to an under- mate of wind stress for low wind speeds. We shall urn to this question in section 10.

he western boundary vortices (*Sargasso Sea*).—Be- nd the countercurrent, the next term in (20) and (21) no longer be neglected. It pivots the asymptotic solution $X = 1$ to $X = 1 - x/r$, and shifts $X'/k = 0$ to $X'/k = -1/kr$ (fig. 2, bottom). The resulting streamlines represent an exponentially decaying vortex trail centered along the axis φ_a (fig. 5). Only the two western vortices need be considered. Accordingly the Sargasso Sea (or any of the other dynamically analogous areas) is a region of relatively sluggish circulation containing a moderately strong anticyclonic vortex at the western side and a weak anticyclonic vortex near its center. The two vortices represent two humps in the sea surface which are separated by a trough with a saddle point in the vicinity of Bermuda. Reid's model (equation 23) gives 10 cm and 2 cm for the peak elevations of the western and eastern humps above the saddle point.



IG. 5. The mass transport stream function in units of 10^{12} ec^{-1} near the western boundary for mean annual zonal winds r the Atlantic. The center line is at 31°N. For comparison with Sargasso Sea circulation, the figure should be distorted by intaining the west–east orientation of the x-axis and rotating y-axis clockwise until the western current and countercurrent parallel to the coast line. (Munk and Carrier, 1950.)

Felber (1934) has analyzed the extensive observational material based on surface drifts of vessels, and his streamlines show a saddle point southwest of Bermuda. A chart of the topography of the sea surface prepared by Defant (1941) on the basis of the *Meteor* observations and preceding observations, does indeed show two humps. Recent detailed observations from closely spaced lowerings of bathythermographs, though inconclusive, are not inconsistent with the above picture.

Central ocean drift.—Away from both boundaries, the equations

$$X_C = 1 - x/r, \qquad X'_C/k = -1/kr, \qquad (20C, 21C)$$

$$M_y = \partial\psi/\partial x = \beta^{-1}\,\text{curl}_z\,\boldsymbol{\tau} \qquad (28)$$

give a broad *constant* drift that compensates for the swift, shallow western currents. Equation (28) was derived by Sverdrup (1947). By dropping the lateral stress term this equation could have been written directly from (6) *without the restriction to zonal winds.* The validity of the theory in mid-ocean has been adequately confirmed by the successful application of (28) to the equatorial currents of the eastern Pacific (Sverdrup, 1947; Reid, 1948a, b).

Eastern coastal strip.—The eastern solution

$$X_E = 1 - \frac{x}{r} - \frac{1}{kr}\left[1 - e^{-k(r-x)}\right], \qquad (20E)$$

$$\frac{X'_E}{k} = -\frac{1}{kr}\left[1 - e^{-k(r-x)}\right] \qquad (21E)$$

represents an exponential slippage zone of width, say, π/k (fig. 3). For $A = 5 \times 10^7$ cm² sec⁻¹ this corresponds to roughly 200 km. This feature is likely to be obscured by meridional wind currents (section 6).

The west–east asymmetry.—The westward intensification of ocean currents[7] has been explained by Stommel (1948) as related to the planetary vorticity. The asymmetry may be expressed as either of the ratios

$$\frac{M_y(WC)}{M_y(C)} = -0.55kr; \qquad \frac{r}{x(WC)} = \frac{\sqrt{3}}{2\pi}kr$$

of the maximum western current to the central drift, or of the width of the ocean to that of the western current. The asymmetry increases with r, decreases with A and φ. For the Atlantic we found $kr \approx 100$.

But the asymmetry is not only one of narrow swift currents versus broad slow currents. The countercurrent and opposing vortices are part of the western dynamic pattern for which there is no counterpart on the eastern side of the oceans. The equivalent mathematical statement is that the real parts of the two complex roots α_1 and α_2 of the characteristic equations (16) are always negative, whereas the real roots α_3 and α_4 are positive. The leftward trend in fig. 1 of α_1' and α_2' with increasing γ shows that the asymmetry becomes even more pronounced for large zonal wind wave-numbers.

These remarks can be interpreted in terms of the differential equation of mass transport (equation 6):

$$\rlap{$\underbrace{\phantom{\text{Lateral stress curl} + \text{planetary vorticity}}}_{\text{western solution}}$}\text{Lateral stress curl} + \underbrace{\text{planetary vorticity} + \text{wind stress curl}}_{\text{central solution}} = 0.$$

In the central and eastern ocean areas the planetary vorticity and wind stress curl have opposite signs, and balance is achieved in which the lateral stress plays a negligible part (except in the unimportant eastern coastal zone). Along the western boundary the planetary vorticity and wind stress curl have the same sign, and the lateral stress curl balances both planetary vorticity and wind stress curl.[8] It can be verified that in this region the wind stress curl is *numerically* unimportant, although it is of course the primary cause of the circulation. The above remarks apply not only to both hemispheres, but also to the cyclonic as well as the anticyclonic gyres. The only way in which the intense currents and the boundary vortices could occur on the eastern side of the oceans would be for the earth to rotate in the opposite sense.

5. Meridional wind solution

Superimposed on the eastern drift we find in vario
oceans rather well developed currents along the easte
boundary, the Benguela, California, Peru and Alas
currents being the outstanding examples. These c
rents are seasonal and vary with the winds. Since th
are not contained in our solution for a zonal wi
circulation we must assume that they depend on t
vorticity provided by the meridional winds.

The procedure to be followed is similar to the one
section (3). The meridional wind stress in the inter
$0 < x < r$ will be written as a sum of terms
$= a \cos mx + b \sin mx + c$, where $m = j\pi/r$, $j =$
2, ··· *etc.* Neglecting the effects of northern a
southern boundaries, $\psi = \psi(x)$, and equation (
reduces to

$$\left(A\frac{d^4}{dx^4} - \beta\frac{d}{dx}\right)\psi_{\mathrm{m}} = -\operatorname{curl}_{z\mathrm{m}} \boldsymbol{\tau} = -\frac{d\tau_{y\mathrm{m}}}{dx}. \quad \text{(6M}$$

The general solution for the m^{th} component of ψ is

$$\psi_{\mathrm{m}} = \frac{\tau_{y\mathrm{m}} - \dfrac{\delta_{\mathrm{m}}{}^3}{m}\dfrac{d\tau_{y\mathrm{m}}}{dx}}{k^3A(1 + \delta_{\mathrm{m}}{}^6)} + e^{-\frac{1}{2}kx}\left[q_1 \cos\left(\frac{\sqrt{3}}{2}kx - q_2\right) + q_3 + q_4e^{-k(r-x)}\right. \quad \text{(15M}$$

where $\delta_{\mathrm{m}} = m/k$ is the ratio between the meridion
wind stress wave number m and the Coriolis-fricti
wave number $k = \sqrt[3]{\beta/A}$, and the q's are constants
be determined from the four boundary conditions (9

In the central and eastern ocean areas ($e^{-\frac{1}{2}kx} \ll$
for a relatively broad meridional wind system ($\delta \ll$
equation (15M) gives

$$\psi(x) = \beta^{-1}[(\tau_y)_x - (\tau_y)_r + k^{-1}(\operatorname{curl}_z \boldsymbol{\tau})_r(1 - e^{-k(r-x)})], \quad \text{(2}$$

$$M_y(x) = \beta^{-1}[(\operatorname{curl}_z \boldsymbol{\tau})_x - (\operatorname{curl}_z \boldsymbol{\tau})_r e^{-k(r-x)}], \quad \text{(3}$$

independent of the wave-number m. Beyond th
eastern coastal strip, (30) reduces again to Sverdrup
equation (28).

6. The California current system

Off the coast of California, perhaps as a consequenc
of the coastal mountain range, the usual situation
for the summer winds south of Cape Mendocino (th
Cape Horn of California) to blow from NNW and t
reach their maximum speed some distance from shor
(fig. 6). Along this wind axis the curl of the wind stres
changes sign, and, neglecting the very small last ter
in (30), the direction of transport changes sign als

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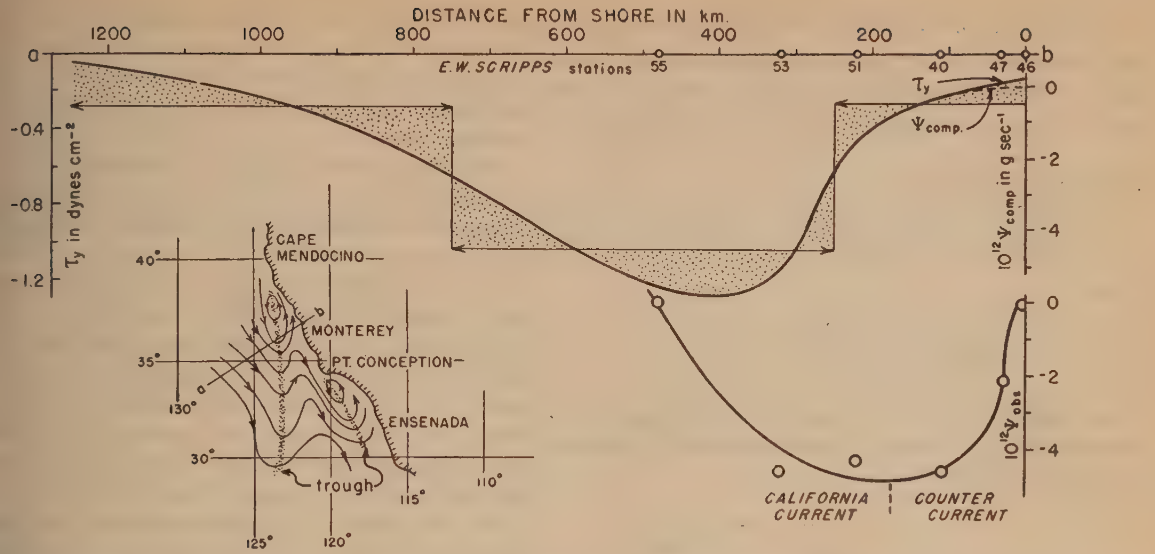
[7] Dynamically it is perhaps more significant to consider the concentration of virtually all the oceans' vorticity against their western shores.

[8] Stockmann (1946) has given a formal solution to (8); that is, he has neglected the important planetary vorticity.



. Meridional winds and currents off California. Horizontal arrows in upper figure show average values of τ_y (left scale) for er the indicated ranges along section a–b, inset. The solid curve is a rough estimate of the actual wind distribution. Except rrow region near shore where a slight modification is introduced by the last term in equation (30), this curve represents also puted mass transport (right scale). The mass transport above the 1000-decibar level from oceanographic observations (Sverd staff, 1942) according to equation (25) is shown by the lower curve. The inset shows dynamic height anomalies, 0 over 1000 based on observations of the *E. W. Scripps* cruise VIII, 10 May to 10 July 1939.

istence of this biologically important counter- is confirmed by an oceanographic section off rey occupied by the *E. W. Scripps* on 11–14 939 (fig. 6). The width of the current during this appeared to have been considerably narrower vould be consistent with average June winds. tal transport of the countercurrent according to about 6×10^{12} g sec^{-1}; according to the oceano- data, 5×10^{12} g sec^{-1}.

boundary between the California Current and current represents a trough in the sea surface fig. 6) which corresponds to the axis of the ly winds. Off the coast of Mexico, both the and wind axis are located further offshore. A trough associated with an eddy south of Pt. tion appears to be related to a second maximum northerly winds extending from Pt. Conception e with San Nicolas Island.

foregoing application of the meridional solution from the limited extent of the wind system and of adequate meteorologic and oceanographic tions. All that can be said is that the average istribution off Monterey is consistent with the ce of a south-flowing current offshore and a current inshore, and that the computed trans- f these currents compare favorably with the ed transports. It should be noted that this -countercurrent system is a consequence of the nd stress curl and dynamically altogether differ- n the current-countercurrent system along the side of the oceans, which has been interpreted undary phenomenon.

7. General solution

Consider now the general field of wind stress

$$\boldsymbol{\tau} = \mathbf{i}\,\tau_x(x, y) + \mathbf{j}\,\tau_y(x, y)$$

associated with large-scale atmospheric circulation, *i.e.*, $\gamma \ll 1$, $\delta \ll 1$. Outside the western and eastern boundary regions, (6) then has the integral

$$\psi_C = -rX_C\beta^{-1}\,\overline{\mathrm{curl}_z\,\boldsymbol{\tau}},$$

where X_C is given by (20C), and

$$\overline{\mathrm{curl}_z\,\boldsymbol{\tau}} = \frac{1}{r - x}\int_x^r \mathrm{curl}_z\,\boldsymbol{\tau}\,dx \qquad (31)$$

represents a *running* average along a segment of latitude between x and the eastern boundary. If variations of the wind stress curl with x in the western and eastern boundary regions are so gradual that ψ fluctuates essentially with $X(x)$, then

$$\psi = -rX\beta^{-1}\,\overline{\mathrm{curl}_z\,\boldsymbol{\tau}} \qquad (32)$$

is a suitable approximation for the entire ocean area. The above condition requires $m \ll k$, which is true by hypothesis. It is in the nature of the (running) average $\overline{\mathrm{curl}_z\,\boldsymbol{\tau}}$ that it should become the less effected by local fluctuations in the wind field the larger the value of $r - x$. This must be at least a partial explanation for the known persistency of zonal currents in the western portion of all oceans.

8. The wind-spun vortex

For a stationary, anticyclonic, circular wind system

$$\tau_\rho = 0, \qquad \tau_\theta = -\Gamma q\rho e^{-q^2\rho^2}, \qquad (33)$$

reaching a maximum stress $\Gamma/\sqrt{2e}$ at a distance from the center $\rho = \frac{1}{2}\sqrt{2}\,q^{-1}$ and zero stress at the center and at great distances, the stream function in the central ocean area (equation 20C, 31, 32) becomes

$$\psi = \beta^{-1}\int_x^\infty \text{curl}_z\,\tau\,dx$$

$$= \tfrac{1}{2}\sqrt{\pi}\,\Gamma\beta^{-1}\{[1 - 2(qy)^2][1 - I] + \tfrac{1}{2}I''\}, \quad (34)$$

where

$$I(q\rho) = \frac{2}{\sqrt{\pi}}\int_0^{q\rho} e^{-(q\rho)^2}\,d(q\rho)$$

is the probability integral and $I'' = d^2I/d(q\rho)^2$. It is assumed that the wind system essentially vanishes some distance from shore.

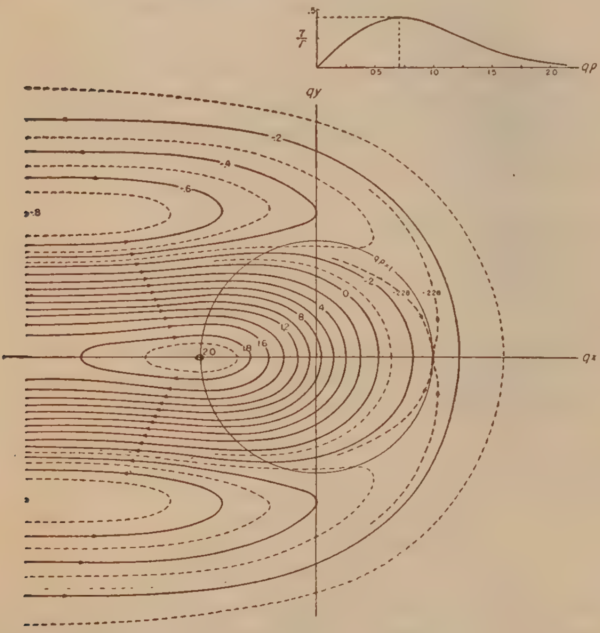


FIG. 7. Mass transport stream lines $\beta\psi/\Gamma$ (nondimensional) resulting from the circular wind system shown above.

The mass-transport streamlines (fig. 7) reveal an anticyclonic vortex centered at $-1/q$, 0, and a trough with a saddle point at $1/q$, 0. The center of the oceanic vortex is thus displaced *west* from the center of the atmospheric vortex by $\sqrt{2}$ times the radius of the maximum stress circle. The net anticyclonic circulation in the vortex is $(2.0 + .228)\Gamma/\beta = 5.2\tau_{\max}/\beta$.

Meteorologic and oceanic observations in the eastern Pacific definitely show a westward displacement of the oceanic anticyclone relative to the Pacific high-pressure area with which it is associated. The magnitudes of the displacement (≈1000 km) and the circulation (≈ 20 × 10^{12} g sec^{-1}) are about 60 per cent of what one might suppose on the basis of the foregoing theory. However, the lack of radial symmetry of the wind system because of its poor development in the weste portion prevents a more quantitative application the theory. The oceanographic observations are i adequate to either confirm or deny the existence of t saddle point.

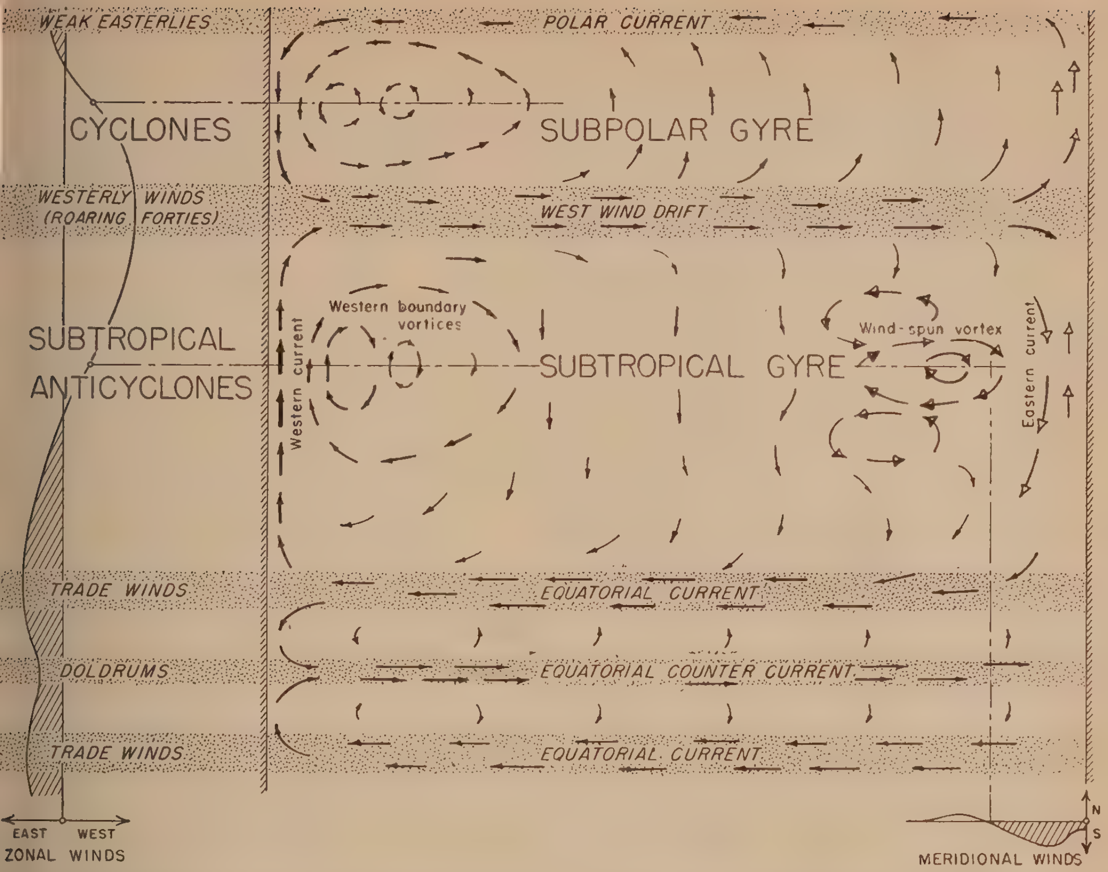
It should be noticed that ψ vanishes at $x = +$ but not at $x = -\infty$. This is the result of havi neglected the lateral stress vorticity in dealing wi the first-order equation (28) which admits only o boundary condition. For large anticyclones ($q/k \ll$ fig. 7 should be a good mid-ocean approximation, a one may expect a *tail* of predominately zonal curre west of the wind system, feeding water into the syst north of the wind axis and expelling it south of t wind axis (vice versa for cyclones), with relativ weak compensation currents farther to the north a south. The effect of lateral stress will be to shorten tail in proportion to the compactness of the wind s tem. For a wind system consisting of alternate clonic and anticyclonic cells over the entire glo Goldsbrough (1935) finds a current system of simi cellular structure but displaced westward relative the wind cells.

9. Classification of ocean currents

In writing this paper we have felt an increasing n for a general nomenclature of ocean currents, ap cable in all oceans regardless of hemisphere, and s gestive of the meteorologic features to which the c rents are so closely related. A possible system is p posed in fig. 8. The corresponding geographic nar for all oceans are summarized in table 3. The circu tion is divided into gyres, which are equivalent scale to the climatic belts. Each gyre contains one two *vortices* equivalent in scale to semiperman pressure centers. It is suggested that the term e be reserved for random features associated w turbulence.

In high (north or south) latitudes the cyclonic *polar* gyre corresponds to the region of the cycl storms, the anticyclonic *subtropical* gyre to the a cyclones. The equatorial currents and countercurr enclose two additional gyres (see fig. 2) correspond to the trades and the doldrums, but these are so nar that they are best not regarded as gyres. A typ gyre is composed of zonal currents to the north south, a strong persistent current and boundary vo on its western side, and a compensating drift in central and eastern portion, upon which a v able eastern current and wind-spun vortex superimposed.

The foregoing classification has chemical and logical implications (see charts IV and VI, figs. 216, and 214, Sverdrup *et al.*, 1942). The subtro gyres, for example, enclose a relatively warm, h


WEAK EASTERLIES
POLAR CURRENT
CYCLONES
SUBPOLAR GYRE
WESTERLY WINDS
(ROARING FORTIES)
WEST WIND DRIFT
Western boundary vortices
Wind-spun vortex
SUBTROPICAL
ANTICYCLONES
Western current
SUBTROPICAL GYRE
Eastern current
TRADE WINDS
EQUATORIAL CURRENT
DOLDRUMS
EQUATORIAL COUNTER CURRENT
TRADE WINDS
EQUATORIAL CURRENT
EAST
WEST
ZONAL WINDS
N
S
MERIDIONAL WINDS

8. Schematic presentation of circulation in a rectangular ocean resulting from zonal winds (filled arrowheads), meridional winds rrowheads), or both (half-filled arrowheads). The width of the arrows is an indication of the strength of the currents. The clature applies to either hemisphere, but in the Southern Hemisphere the subpolar gyre is replaced largely by the Antarctic polar Current (west wind drift) flowing around the world. Geographic names of the currents in various oceans are summarized e 3.

of water, poor in phosphates, relatively low in ical activity, and blue in color ('blue is the desert of the sea'). The boundaries of the gyres are d by remarkably pronounced horizontal gradin all these variables. The western boundary es are biologically unique in that they represent ly regions in the open sea where freely floating sms in the sunlit zone can be expected to remain y length of time in a uniform environment. Of egions, named *halostases* by biologists, the best is the Sargasso Sea, named after its concentraf *Sargassum*, or *Gulf Weed*, a brown alga charac- of subtropical regions. The six remaining ases (table 3) are equivalent dynamically to the sso Sea and it would not be surprising were they istinguished by concentrations of freely floating sms with narrow environmental tolerance.

iscussion and conclusions

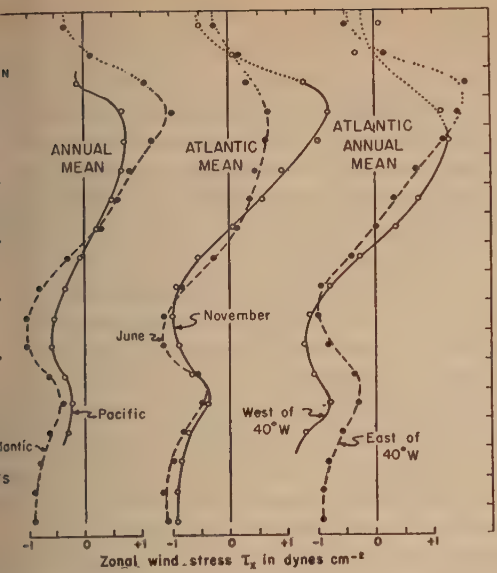
classification of ocean currents in table 3 is put with some hesitation, as it is almost certain to e some unwarranted oversimplification. Additional data on currents and wind stress are likely to lead to revisions. Particularly in the southern oceans the boundary conditions for the subpolar gyre differ radically from those we have considered, and the dynamics of the Antarctic Circumpolar Current is not properly understood. But even so, a preliminary table is helpful in interpreting the main features in the ocean circulation and, what is more important, to point out reasons for essential *differences* in different oceans.

For example, the Gulf Stream and Brazil Current occupy equivalent positions in the North and South Atlantic, yet the Gulf Stream has about ten times as much transport. According to (26) and table 2 this difference is due chiefly to the larger wind stress curl in the North Atlantic. Differences in wind stress curl can be ascribed to the northward displacement of the climatic equator relative to the geographical equator, which reduces the distance between the trades and the westerlies in the northern hemisphere to about 60 per cent of that in the southern hemisphere. The displacement of the trades in turn seems to be related to the unequal distribution of land and sea in the two hemi-

TABLE 3. The general ocean circulation.

	Classification (see fig. 8)		North Atlantic	South Atlantic	North Pacific	South Pacific	North Indian	South Indian
↑ Subpolar Gyre	Polar Current	(z)		p ?	p	p (w.)		p
			E. Greenland (3)					
	Western C.	(z)	Labrador (6) ?	Falkland	Oyashio	a		a
	W. bdry vortex	(z)	p ? (50°N, 50°W)	a ?	?	a		a
	Eastern C.	(m)	Norwegian (3)	a	Alaska	a		a
	Wind-spun vortex	(z, m)	a	a ?	Gulf of Alaska	a	A	a
					Aleutian (15)		S I	
↓ ↑ Subtropical Gyre	West Wind Drift	(z)	Gulf Stream S. N. Atlantic (38)	West wind drift	Kuroshio S. N. Pacific (20)	West wind drift	A	West wind drift
					Kuroshio Ext. (65)			
			Gulf Stream (70)					
	Western C.	(z)		Brazil (7)	Kuroshio (23)	E. Australia ?		Agulhas (25)
			Florida (26)					
	W. bdry vortex	(z)	Sargasso Sea	p	p	p		p
	Eastern C.	(m)	Canary ?	Benguela (16)	California (15)	Peru (13)		p (v)
	Wind-spun vortex	(z, m)	Azores vortex	p (30°S, 5°W)	E. Pac. vortex	p (30°S, 100°W)		p (30°S, 95°E)
↓	Equatorial Current	(z)	N. Equat. C. (32)	S. Equat. C.	N. Equat. C. (45)	S. Equat. C.	N. Equat. C.	S. Equat. C.
	Equat. Counter C.	(z)	Equat. C. C. (4) ⟵	a	Equat. C. C. (25) ⟵	a	a ⟶	Equat. C. C.

a: absent; p: present, but unnamed; m: related to meridional winds; S: system; v: variable; w: weak; z: related to zonal winds.
Figures in parentheses give mass transport in 10^{12} g sec^{-1} estimated from oceanographic observations.



9. Distribution of zonal wind stress with latitude. Note the dinal asymmetry over the North Atlantic. In the region of Greenland, where observations are lacking, the wind averages have been corrected for this asymmetry. The lines indicate uncertainty because of lack of sufficient tional data.

es. One is tempted, then, to trace the preponder- of the great Gulf Stream and Kuroshio systems heir southern counterpart to the excess of water- ed area in the southern hemisphere.

ferences in circulation between the North At- and North Pacific can be at least partly ascribed e greater intensity and northward displacement e Atlantic zonal winds, especially during winter). The circulation in the subpolar gyre of the Atlantic is complicated by two related factors: the northern land boundaries and the axis of the rly winds are further north in the eastern than entral and western portion. This may be the n why the western current of the subpolar gyre is n up into two parts (Sverdrup *et al.*, 1942, pp. 66): the East-Greenland current flowing at an ge longitude of 30°W from 80°N to 60°N; and the dor current at 60°W, flowing from 60°N to 40°N. e wind stress pattern over the subpolar gyre is y a reflection of the traveling cyclones, and one expect a certain adjustment of the ocean circula- o the frequency and paths of these cyclones. The t of such an adjustment depends on the time ants of the ocean circulation. Observational evi- indicates that the adjustment to individual s is not a major one, yet that the main currents veal seasonal fluctuations. The time constants r, therefore, to be of the order of weeks, perhaps hs. Thus ocean currents might represent a con- nt method of obtaining time averages of atmos- c circulation. For example, the intensity of the Stream (perhaps estimated from tide records) could be related to the mean wind vorticity in the region of subtropical anticyclones over the Atlantic.

The foregoing statement is somewhat at variance with the usual assertion that the Gulf Stream is *caused* by the trades. Rather it is related to the vector *difference* between the trades and the westerlies, or, strictly speaking, to the mean value of the wind stress curl at the latitude in question. It is at least conceivable that an increase in the velocity of the trades be confined to a narrow band of latitude, and that the wind stress curl and the Gulf Stream at, say, 30°N remain unchanged. This is, however, unlikely for physical reasons as the mechanism responsible for the transfer of momentum from the westerlies to the trades would tend to distribute such an increase over the entire subtropical zone.

The validity of our statement that the intensity of the western current be proportional to the wind stress curl at the latitude in question depends on the approximations involved in neglecting the inertial terms in (1). Rossby (1936) has developed a *wake-stream theory* of the Gulf Stream in which the inertial terms play a predominant part. The theory has many attractive features. It explains the increase downstream in width and mass transport, the existence of an observed countercurrent on the *western* edge of the Gulf Stream, and a jet-like current profile which appears to be in accord with recent observations (Iselin and Fuglister, 1948).

In order to estimate the magnitude of the inertial terms it is necessary to specify the distribution of density and velocity with depth. Using Reid's exponential model for the density (23) and a similar law for the velocity:

$$v = v_0 \text{ for } -z \leqslant h', \qquad v = v_0 e^{1+z'/h} \text{ for } -z \geqslant h',$$

one obtains the expression

$$\frac{3}{8}\frac{1}{\rho_0 h'}\nabla \times (\mathbf{M}\cdot\nabla)\mathbf{M}, \tag{35}$$

to be added to the left side of the differential equation of mass transport (6). The ratio

$$\frac{\sqrt{3}}{4}\frac{rk^2n^2\tau_{\max}}{\rho_0 h'\beta^2}e^{-\frac{1}{2}kx}\cos\left(\frac{\sqrt{3}}{2}kx+\frac{\pi}{6}\right), \tag{36}$$

of (35) to the planetary vorticity is small except along the inshore edge of the western current, where it may reach unity. It seems likely that some of our conclusions will be modified in the sense prescribed by Rossby.

This investigation has served to emphasize the fundamental importance of the wind stress *curl* rather than of the wind stress *vector* in determining the transport of ocean currents in meridionally bounded oceans. For example, the circulation shown in figs. 2 and 6 is in no ways modified by shifting the zero axis of the wind stress curve. It so happens that in the subtropical zone the inflection point of the zonal wind stress curve falls close to where the wind stress changes sign, and it has been tacitly assumed in most textbooks that the change from a westward to an eastward current is related to a similar change in wind direction. This general misconception probably explains the difficulty in interpreting instances where the current runs against the wind, such as the California Countercurrent, the Point Barrow Current, and most important of all, the Equatorial Countercurrent. In the case of an irrotational wind field, such as a uniform west wind, over an ocean bounded on its western and eastern sides, it follows from (4) and (22) that $\psi = 0$, $\nabla P = \boldsymbol{\tau}$, *i.e.*, that there is no circulation and that the stress is balanced by the pressure distribution resulting from the piling up of water against the lee shore. With the important exception of the Antarctic Circumpolar Current, which has no major meridional boundaries, it can be stated that *permanent ocean currents are related to the rotational component of the wind stress field over the ocean. These ocean currents would vanish were the wind stress field irrotational.*

Finally we may examine the question of why the computed transports of the Gulf Stream and the Kuroshio current amount to only about one half the observed values (table 2). It does not seem reasonable that the oceanographic observations should be off by more than, say, 20 per cent, nor that the theoretical expression (26) for the transport should account for the discrepancy, since it is almost independent of the eddy viscosity and the shape of the ocean basin.

Maury and others have ascribed the North Atlantic circulation, in particular the Gulf Stream, to differential heating between equator and pole, to the freezing of ice, and to other processes that make up the *thermohaline* circulation. If we assume that the circulation were half wind-driven, half thermohaline, it would be a strange coincidence that the general *pattern* of the circulation, such as the boundaries of the gyres, should conform so closely to the general atmospheric circulation. Furthermore, Fuglister[9] has found a high correlation between *variations* in the current with variations in the wind. It should also be noted that the thermohaline circulation insofar as it is related to the outflow of river water along the Atlantic seaboard would tend to reduce rather than to strengthen the Gulf Stream. It would seem therefore that the subtropical gyre, and probably also the subpolar gyre, are predominantly wind-driven.

Methods for computing wind stress from the observed wind speeds according to the equation

$$\boldsymbol{\tau} = C_D \rho_{\mathrm{air}} U^2$$

are discussed by Reid (1948a) and in SIO Oc
graphic Report 14.[10] Underestimates of $\boldsymbol{\tau}$ may f
all result from underestimates in the wind spee
the climatological charts from which the appro
averages were taken. The preponderance of c
stations, and the tendency of ships at sea to
regions of high wind, would lead to consistent e
but these cannot account for more than a fract
the discrepancies. The weakest link is the drag
cient C_D which is based on measurements of
storm tides, and a few other measurements (Sve
et al., 1942, pp. 489–500). In accordance with the
presently accepted we have assumed $C_D = .00$
high wind speeds, $C_D \approx .008$ at low speeds, wit
discontinuity occurring at Beaufort 4 (Munk,
In the trade-wind belt of the eastern Pacific, whe
winds are predominantly Beaufort 4 and a
Sverdrup (1947) and Reid (1948a) have obt
satisfactory agreement between computed an
served transports. Supposing a value of .0026
applicable at all wind speeds, then the effect
southwesterly winds over the eastern Atlantic
make itself felt in a much higher meridional win
tor (table 2), and it can be demonstrated tha
discrepancy between computed and observed
ports could be largely accounted for. We are the
led to propose a higher value of C_D at low
speeds.[11] The transports of the Gulf Stream
Kuroshio current are, after all, probably as go
indicator of the overall stress exerted by the win
the ocean as any of the measurements on whic
value of C_D is now based.

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fig. 41.

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[9] F. C. Fuglister, "Annual variations in current speeds in the Gulf Stream system," *Woods Hole Oceanographic Institution Technical Report No. 15* (unpublished), 1948.

[10] Scripps Institution of Oceanography, "The field of mean
stress over the North Pacific Ocean," Oceanographic Repo
14 (unpublished).

[11] Neumann (1948) claims on the basis of his analysis of
and North Sea tilt that the drag coefficient actually *inc*
with decreasing wind speed. His average value for C_D perta
to Beaufort 3 is in excess of .0040.

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Reprinted from COPEIA, 1950, No. 3, September 5

AN INSHORE RECORD OF THE BATHYPELAGIC FISH, *CHAULIODUS MACOUNI* BEAN, FROM BRITISH COLUMBIA.[1]—A specimen of *Chauliodus macouni* was taken in a shrimp trawl off the mouth of the Fraser River in the Strait of Georgia during April, 1947, at a depth of 40 fathoms. This record is unique, since the viper-fish is recognized as a bathypelagic species. The specimen is deposited in the collections of the Pacific Biological Station of the Fisheries Research Board of Canada.

The first British Columbian specimen of this species, the basis of the original description, was taken on August 31, 1888, by the United States Fish Commission Steamer "Albatross," off Cape St. James, Queen Charlotte Islands, at Station 2860, 51° 23′ N. Lat., 130° 34′ W. Long., at a stated depth of 876 fathoms (Bean, 1890, Proc. U. S. Nat. Mus., 13: 44). Since then a total of 367 specimens have been recovered in tow-nets by the International Fisheries Commission off the west coast of Vancouver Island, off the Queen Charlotte Islands and in the Gulf of Alaska, northward and westward to the Sanak Islands (Chapman, 1940, Occ. Pap. B. C. Prov. Mus., 2: 5). This species was taken by the "Albatross" during the year 1890, at Station 3340, south of the Alaska Peninsula, at a depth of 695 fathoms, and at Station 3347, off the northern coast of Oregon, at a depth of 345 fathoms (Gilbert, 1896, Rept. U. S. Comm. Fish., 1893: 402). It was also taken off the coast of California in 1904 by the "Albatross" in Monterey Bay, and off Santa Catalina and San Clemente Islands (Gilbert, 1915, Proc. U.S. Nat. Mus., 48: 321).

As the name implies, the fanged viper-fish has very long teeth. There are 4 very long anterior teeth on the premaxillary and excessively long anterior teeth on the mandibles. None of these teeth are received within the mouth. In addition to the canines, small, fine, pointed teeth occur in one row on the maxillaries and mandibles and in two rows on the palatines. The cleft of the mouth reaches beyond the eye. The dorsal fin is situated well in front of the pelvics and the first dorsal ray is produced into a filament about one-fourth as long as the body. The narrow pelvics are much longer than the head.

The counts and measurements are within the limits recorded by Chapman (*op. cit.*) for 13 specimens selected at random from the collection of the International Fisheries Commission. Standard length 78 mm. Length to origin of anal fin about 64.5 mm. Distortion of the body prevents precise measurements of this and some other body proportions. Predorsal length, 19.5 mm. Head length, 12.8 mm. Length of snout, 3.0 mm. Diameter of eye, 2.9 mm. Proportions in standard length: snout to origin of dorsal, 4.0; length of head, 6.1; snout to origin of pelvics, 2.36; snout to anal, 1.2. Proportions in length of head: diameter of eye, 4.4; length of snout, 4.2. Fin rays: D. 6; A. 11; P. 12; V. 7. Number of photophores: O-V, 18; V-A, 25; total in lateral row, 43; I-P, 9; P-V, 19; V-A, 26; A-C, 11; total in ventral row, 65; branchiostegal series, 19.

No help in the identification of this specimen is provided by Ege's (1948, Dana Rept., 31: 1–148, figs. 1–9, pls. 1–3) revision of the genus, which was based largely on material collected by the "Dana" during its cruise around the world in 1928–30 and on previous "Dana" expeditions. From a single specimen taken off the Gulf of Panama in the open Pacific, Ege concluded that *Chauliodus macouni* should be reduced to subspecific rank under the name *Chauliodus sloanei macouni*. He presumed that the specimens described by Bean (*op. cit.*), Gilbert (*op. cit.*) and Chapman (*op. cit.*) represented the temperate form of this subspecies and that the single specimen taken by the "Dana" represents the tropical form of the subspecies. These forms, which parallel those of other subspecies, were distinguished by certain numerical values.

Although the specimen from the Strait of Georgia agrees with the 13 specimens described by Chapman as *Chauliodus macouni*, it does not agree with the synopsis and diagnosis given by Ege for "*Chauliodus sloanei macouni*": the length to the origin of the anal fin, without the head, is 66.3 rather than 67.3 to 72.8 per cent of the standard length; the length of the foremost premaxillary tooth is 78 rather than 51.5 per cent as long as the largest premaxillary tooth; the number of organs in each section of the main row of smaller photophores, in the area between the longitudinal rows of large photophores, is 2 to 3 rather than 5. Further study is needed to determine whether, in line with these observed differences, the single specimen from the Strait of Georgia is not referable to *C. macouni,* or whether the one specimen available to Ege does not represent this species. In particular, the specimens in the collection of the International Fisheries Commission should be re-examined to redefine the diagnostic characters of *C. macouni,* particularly in regard to the section of the main row of smaller photophores in the area between the longitudinal rows of larger photophores (the character most strongly emphasized by Ege). Until such studies have been made, it is recommended that *C. macouni* be retained as a full species.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 467.

Sincere thanks are due Dr. Carl L. Hubbs for advice in the study of the specimen and in the preparation of the manuscript. The author is a graduate student on educational leave from the Fisheries Research Board of Canada.—W. E. BARRACLOUGH, *Scripps Institution of Oceanography, La Jolla, California.*

Contribution No. 468

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Sea Temperatures, Hawaiian Island Area[1]

A Study of the Distribution of Ocean Temperatures in the Surface and Subsurface Based upon Bathythermograph Observations

DALE F. LEIPPER AND ERNEST R. ANDERSON[2]

INTRODUCTION

SINCE 1940 the supply of available sea-temperature information has been greatly increased through the use of the bathythermograph (Spilhaus, 1940), an instrument which may be lowered from moving vessels to provide a continuous trace of temperature against depth. The temperature values are usually accurate to within ± 0.3° F. Greatest depths attained are approximately 180, 450, or 900 feet, depending upon the type of bathythermograph used. A detailed sea-temperature study of the Hawaiian Island area (the area from 15° to 30° north latitude and 150° to 165° west longitude) was prepared by the Bathythermograph Section at Scripps Institution of Oceanography (Leipper and Anderson, 1948; Hiatt, 1948). This study, made from 5,407 observations, is the basis of the summary presented here. A similar study was made in the Philippine Island area (Leipper and Wood, 1947) but has not yet been published.

Purpose of the investigation

The purpose of this investigation is threefold: (1) to show the horizontal and vertical distribution of temperature; (2) to show the amount of data that is available an
is distributed; and (3) to further th
opment of a model temperature-dis
study that may in the future be used
regions.

Availability of bathythermograph da

The file of bathythermograms
Pacific and Indian Oceans is maint
Scripps Institution of Oceanography,
California, and at the U. S. Hydr
Office, Washington, D. C. Copies
vations may be requested from the
graphic Office.

Acknowledgments: Clerical and
assistance was furnished by Misses
V. Wilburn, M. Hunter, M. Oakes,
bridge, and Mrs. B. Rimbach. Draf
done by Mrs. M. Robinson and phot
work by Mr. P. Williams.

DISTRIBUTION OF BATHYTHERMO

The bathythermograph observati
for this investigation cover the per
January, 1941, to November, 1947
bathythermograms available, 5,377
able for use.

The time distribution of the bath
grams is shown by Tables 1, 2, ar
lowing the text. Table 1 shows th
percentage distribution; Table 2,
monthly percentage distribution; a
3, the monthly percentage distributi
ferent years. The space distributio
bathythermograms is shown in F
(Figures appear at the end of the
tabular material begins on page 23

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[1] Contributions from the Scripps Institution of Oceanography, University of California, New Series No. 468. This work represents results of research carried out by the University of California, under contract with the Office of Naval Research and the Hydrographic Office of the Department of the Navy.

[2] Now associated with the Department of Oceanography, Agricultural and Mechanical College of Texas, College Station, Texas, and the Oceanographic Branch, Navy Electronics Laboratory, San Diego, California, respectively.

groups of cruises, designated as the
Ɔ cruises, were made near the entrance
l Harbor during 1944 and the early
1945. The following tabulation shows
es of these cruises as well as the num-
athythermograph observations taken.

H AND *Q* CRUISE DATA

DATE	NUMBER OF BATHY-THERMOGRAMS
2/24/44– 3/29/44	60
3/29/44– 4/22/44	60
4/23/44– 5/14/44	60
5/15/44– 6/26/44	60
6/27/44– 9/ 4/44	60
9/15/44–11/13/44	60
11/14/44– 2/12/45	60
2/12/45– 2/20/45	7
3/13/44– 3/29/44	42
3/29/44– 4/17/44	56
4/17/44– 5/ 6/44	57
5/ 6/44– 5/30/44	60
6/ 1/44–10/ 9/44	108
11/16/44– 2/20/45	63

NTAL TEMPERATURE DISTRIBUTION

ıtal temperature distribution based on s by 1-degree quadrangles of latitude gitude

ıorizontal distribution of average tem-
e at the surface and at depths of 100
)0 feet, and 300 feet is shown in
2 to 13 for each of the 12 months
year. March and September average
ıtures were, respectively, lowest and
of the year. June and December were
having temperature distributions typ-
months of transition.

eparing the monthly average temper-
harts, the following procedure was
At each depth level, all available tem-
es for each 1–degree quadrangle were
d by months. To obtain time conti-
he monthly averages for each quad-
where there were sufficient data were
against time, and a curve, smoothed
, was drawn through the points.
y average temperatures were then read from this smoothed curve. The values for each month were plotted on a map by position, and the isotherms were drawn.

The ocean current systems which are present affect the horizontal temperature distribution. In March the southern portion of the Hawaiian Island area is under the influence of the northeast trade winds with a resulting ocean current toward the west known as the North Equatorial Current. In the northerly portion of the area the North Pacific Current flows toward the southeast. Between these two currents as shown in Figure 14 is a region where the flow is variable (Sverdrup, Johnson, and Fleming, 1946: 723, appendix, Chart VII). This region coincides with the region where the pattern of isotherms is most irregular, as shown in Figures 2 to 13.

The extremes of average temperature

For each month of the year, at particular depths, the maximum average monthly temperature occurring in any 1-degree quadrangle of the Hawaiian Island area was selected. Similarly, the minimum average was obtained. These, together with the differences between them, are presented in Table 4 at several depths for each month. At the surface and at 100 feet, the differences are smaller during the summer than during the winter. At 200 and 300 feet, the differences appear to be almost constant.

Table 5 (page 233) shows results of analysis of the smoothed annual temperature-variation curves which were drawn for each 1-degree quadrangle as explained earlier. An examination of the table shows that the minimum occurred the greatest percentage of the time in March at all levels except 300 feet; and the maximum, in September at all levels except 300 feet. At 300 feet the minimum occurred most often in April and the maximum most often in October.

Figures 16 and 17 present the maximum and minimum monthly average temperatures, respectively, for the surface and the 100-, 200-, and 300-foot levels. To obtain Figure 16, the highest monthly average temperature at each depth in each quadrangle was plotted, regardless of the month or year in which it occurred, and isotherms were drawn. Figure 17 was prepared similarly for lowest monthly average temperatures.

The highest single surface temperature recorded in the Hawaiian Island area was 90° F. at 19° N and 157° W in August, 1942, while the lowest single temperature recorded was 60.9° F. at 28° N and 163° W in January, 1947.

Annual sea temperatures at a depth of 400 feet

As is apparent in Figures 22 and 27, sea temperatures at a depth of 400 feet have only a small annual variation. Values for all months of the year have therefore been averaged together by 1-degree quadrangles to obtain the annual average. These annual averages were plotted by position and isotherms drawn (see Figure 15). This figure, when compared with Figures 22 and 27, indicates that at 400 feet the variation of sea temperature with position greatly exceeds the variation with time.

Comparison of average temperatures in different years

Figure 18 compares the annual variation of temperature at the surface, 100 feet, 200 feet, and 300 feet for each of the years 1943 to 1947 with the average annual variation for all years combined. There is considerable difference between the curves representing different years. The year 1943 was warmer than average at the surface and 100 feet. Not enough data were available to show the deviation at 200 feet and at 300 feet in this year. The year 1944 was virtually an average year at the upper two levels, while at the two lower levels there was some variation from the average. The year 1945 was definitely a warmer-than-average year in the upper two levels, while in the lower two it was generally warmer with a few months colder than age. The first part of the year 1946 wa initely warmer than average, while the part of the year was colder than avera all levels. The year 1947 was a colder average year at all levels with the dev being the greatest in the upper 100 fe

Average temperature in the vicinity of

Figure 19 shows the temperature dis tion in the vicinity of Oahu for the su 100 feet, 200 feet, and 300 feet. Th therms at each depth are based upon av computed for each 10-minute quadran latitude and longitude. Thus the deta the average temperature distribution Oahu are shown. In this region many vations are available and detailed inform may have practical value.

VERTICAL TEMPERATURE DISTRIBUT

Southwest-northeast cross section

Figures 20 and 21 present av southwest-northeast temperature-depth tions for winter and summer months, r tively. All available bathythermogran the two periods of time, and within the denoted in Figure 1, were used to obta averages at various positions and d These averages form the basis of the se

Monthly average temperature-depth cu

Figure 22 shows curves through the age temperatures at different depths fo degree quadrangle covering the area 2 25° N and 155° to 160° W. These were obtained by averaging all ava temperatures for each month at 1 depth intervals down to 100 feet and foot intervals down to 425 feet, pl these averages against depth, and j the points. Such curves do not sho typical temperature-depth structure b of smoothing which occurs in averaging number of temperatures included in the age is shown beside each point.

ure 23 shows the average temperature- curves for two specific points. The s labeled "H" are taken from *H* cruise These cruises consisted of 386 bathy- ograph observations from March, 1944, bruary, 1945. All data were collected ° 18′ N and 157° 53′ W, approximately mile south southwest of Honolulu in eet of water. These data were averaged ner by months with the results as shown figure. The curves labeled "Q" are taken *Q* cruise data. These cruises consisted 27 bathythermograms from February, to February, 1945. The station was d at 21° 18′ N and 157° 58′ W about miles due south of the entrance to Pearl or in about 600 feet of water.

ese two stations are located approx- ly 5 miles apart, and the data were taken g the same year. It is interesting to note luring the months of March and April verage curves were identical, but during ther months the *H* cruise data showed ciably lower temperature at all depths.

al bathythermograms

ure 24 contains copies of actual bathy- iograms selected as typical of a northern a southern portion of the area under for the months of March, June, Sep- er, and December. These single records several prominent features which are pparent in curves drawn through average eratures at selected depths. One of these res is the deep layer of nearly isothermal which is present on several of the in- ual curves. Another is the strong ther- ne. Each of these characteristics is typ- of nearly all individual bathythermo- s in this area but the process of aver- and the decreasing frequency of tem- ure readings with depth causes them to pear from the average temperature-depth s. Thus it is desirable to consider typ- single observations as well as average s.

Depth of the virtually isothermal layer

The average depth of the virtually isothermal layer for summer and winter periods is shown in Figure 25. The charts were prepared by reading from the bathythermograms the layer depth to the nearest foot and averaging the results by 1-degree quadrangles. These data were then plotted, and isolines of depth were drawn. The virtually isothermal layer is, on the average, deeper than the 180-foot maximum depth for the "shallow" bathythermograph; hence, the "deep" bathythermographs are the only ones that reach the thermocline. As a result, only 40 per cent of the total number of bathythermograms available for this study were used in establishing the layer depth. Two conclusions may be drawn from Figure 25: the layer depth varies considerably with position; and during the winter the depth is greater than during the summer.

An attempt was made to draw layer-depth charts for each month of the year. Although many observations were available, the variability within any given month and any given quadrangle was so great that it was not possible to draw isolines that exhibited good continuity.

Diurnal and annual variation of temperature

In August, 1941, the U.S.S. "Pyro" took bathythermograph observations every hour in the area 21° to 34° N and 138° to 157° W. These data were analyzed by H. U. Sverdrup and others to determine the diurnal variation of temperature. Figure 26 shows the results of this analysis.

The wind-stirred layer at the time of these observations was approximately 120 feet thick with 75° F. as the average temperature of the layer. Between the surface and 120 feet the temperatures were read at 30-foot intervals. The temperature differences between 120 feet and each other level were determined and plotted. The figure shows that the upper layer is nearly isothermal during the early morning, but that the vertical gradient increases as the effect of solar radiation is felt. The time of maximum temperature occurs later at greater depths because time is required for heat to reach these depths by conduction.

The annual variation of temperature at subsurface depths in the area 20° to 25° N and 157° to 160° W is shown in Figure 27. The maximum temperature occurs at 400 feet approximately 1.3 months later than at the surface. A secondary maximum is indicated in January. The maximum shown at 400-foot level in April is probably not a real feature but one due to the uneven frequency distribution of observations.

ADDITIONAL DATA AVAILABLE

In addition to what has been published here, certain further investigations have been made and results are available from the Scripps Institution of Oceanography. Among these results are charts of the distribution of observations by months and hydrographic station data.

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——— and WILLIAM WOOD. 1947. perature and salinity of Philippine *Scripps Inst. Oceanography, Oceanog Rpt.* 4. [Mimeographed.]

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TABLES

TABLE 1
DISTRIBUTION OF BATHYTHERMOGRAMS BY YEARS

YEAR	PERCENTAGE
1941	3.2
1942	2.5
1943	16.0
1944	43.0
1945	15.1
1946	11.7
1947	8.6

TABLE 2
DISTRIBUTION OF BATHYTHERMOGRA BY MONTHS

MONTH	PERCE
January	7
February	1
March	1
April	11
May	9
June	6
July	7
August	9
September	9
October	6
November	6
December	4

TABLE 3
Distribution of Bathythermograms by Months in Different Years
(All figures are given as percentages.)

MONTH	1941	1942	1943	1944	1945	1946	1947
ry	0.0	0.0	0.3	5.8	23.4	2.1	7.0
ary	1.2	13.4	18.4	7.3	13.6	7.0	7.8
	5.3	0.0	13.0	8.7	9.4	1.7	30.0
	0.0	11.2	13.2	12.0	10.2	9.2	15.9
	2.4	22.4	9.5	14.1	2.8	2.9	11.3
	1.8	11.9	1.8	7.8	3.4	5.1	17.6
	3.5	0.0	5.0	7.2	6.9	9.1	10.4
t	42.9	14.9	3.6	10.3	8.3	16.7	0.0
nber	2.9	9.7	12.1	8.0	6.3	20.5	0.0
er	10.6	0.0	7.0	7.0	3.8	11.0	0.0
nber	24.7	0.0	5.0	6.6	5.4	8.7	0.0
nber	5.3	16.4	11.0	5.3	6.4	5.9	0.0

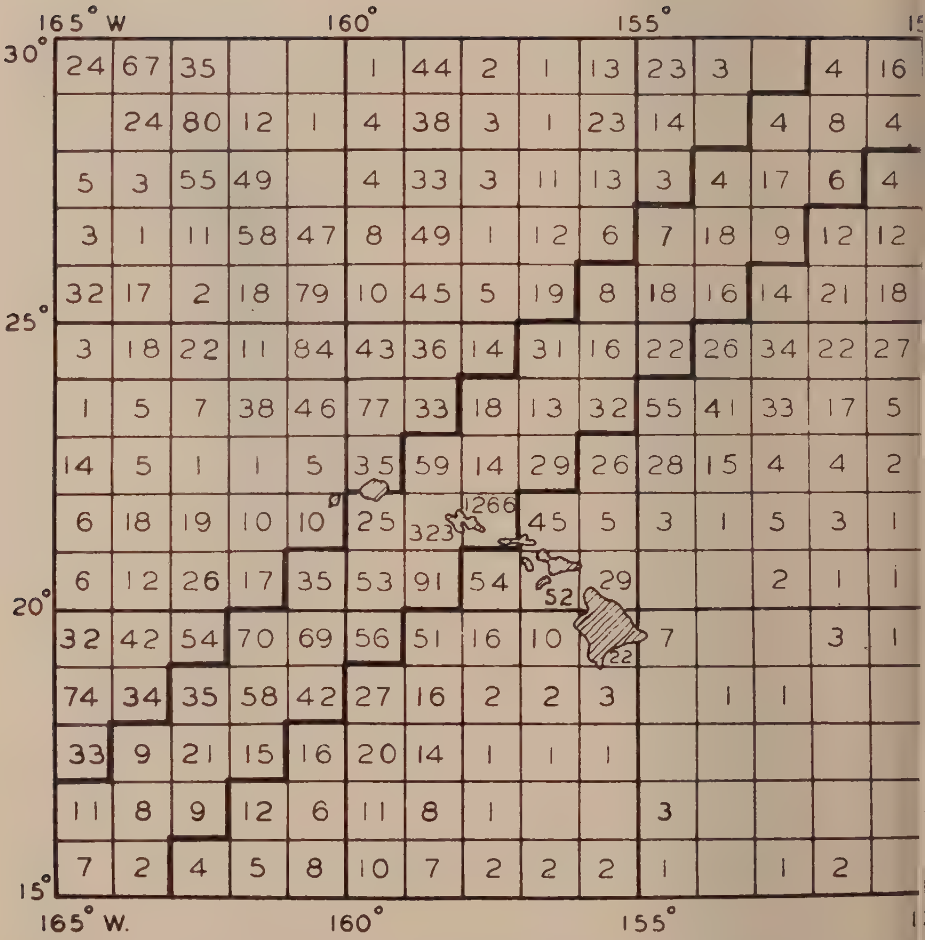
TABLE 4
Maximum and Minimum Monthly Average Temperatures at Different Depths

	MAXIMUM				MINIMUM				DIFFERENCE			
in feet	0	100	200	300	0	100	200	300	0	100	200	300
ry	80	79	78	78	68	68	66	64	12	11	12	14
ary	79	78	78	77	67	66	65	64	12	12	13	13
	78	77	77	76	66	67	64	64	12	10	13	12
	78	77	77	76	68	68	64	64	10	9	13	12
	79	78	78	77	70	69	66	64	9	9	12	13
	80	80	79	77	74	71	68	64	6	9	11	13
	82	80	80	78	76	73	66	64	6	7	14	14
t	82	81	81	79	77	75	68	66	5	6	13	13
nber	82	82	81	80	77	76	67	67	5	6	14	13
er	82	82	82	80	76	75	68	66	6	7	14	14
nber	82	81	81	80	72	72	68	67	10	9	13	13
nber	80	80	80	79	70	70	67	66	10	10	13	13

TABLE 5
nths in Which Maximum and Minimum Temperatures Occurred Most Often on Smoothed Annual Variation Curves Which Were Drawn for Each 1-Degree Quadrangle

MINIMUM			MAXIMUM		
th	Month	Frequency	Depth	Month	Frequency
et		*Per cent*	*Feet*		*Per cent*
e	March	56.4	Surface	September	64.5
	March	57.9	100	September	71.0
	March	46.6	200	September	51.1
	April	39.0	300	October	40.7
	March	48.9	All	September	54.9

FIGURES



24	67	35			1	44	2	1	13	23	3		4	16
	24	80	12	1	4	38	3	1	23	14		4	8	4
5	3	55	49		4	33	3	11	13	3	4	17	6	4
3	1	11	58	47	8	49	1	12	6	7	18	9	12	12
32	17	2	18	79	10	45	5	19	8	18	16	14	21	18
3	18	22	11	84	43	36	14	31	16	22	26	34	22	27
1	5	7	38	46	77	33	18	13	32	55	41	33	17	5
14	5	1	1	5	35	59	14	29	26	28	15	4	4	2
6	18	19	10	10	25	323	1266	45	5	3	1	5	3	1
6	12	26	17	35	53	91	54	52	29			2	1	1
32	42	54	70	69	56	51	16	10	22	7			3	1
74	34	35	58	42	27	16	2	2	3		1	1		
33	9	21	15	16	20	14	1	1	1					
11	8	9	12	6	11	8	1			3				
7	2	4	5	8	10	7	2	2	2	1		1	2	

FIG. 1. Distribution of bathythermograph observations processed prior to November, 19

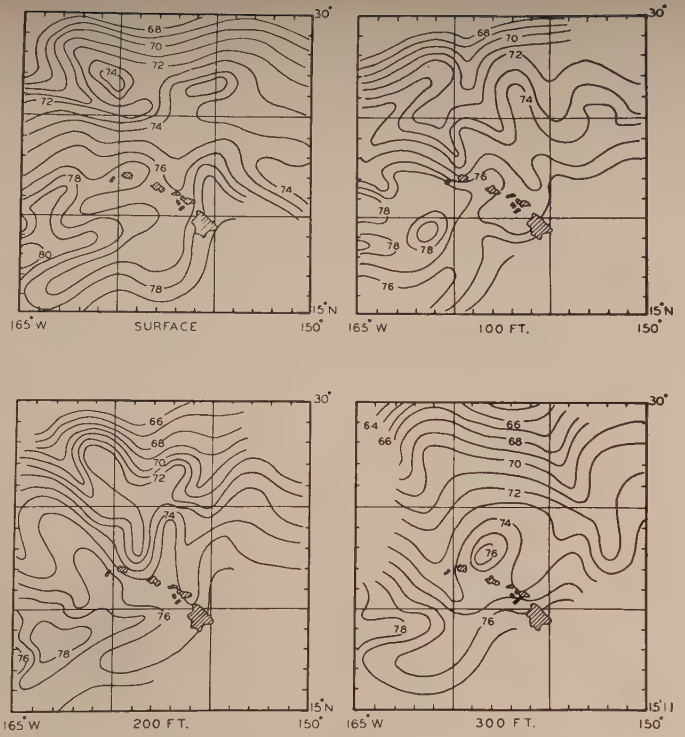

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
64
66
68
70
72
74
76
78
80

FIG. 2. JANUARY, average sea temperatures (° F.) at selected depths (1941–1947).

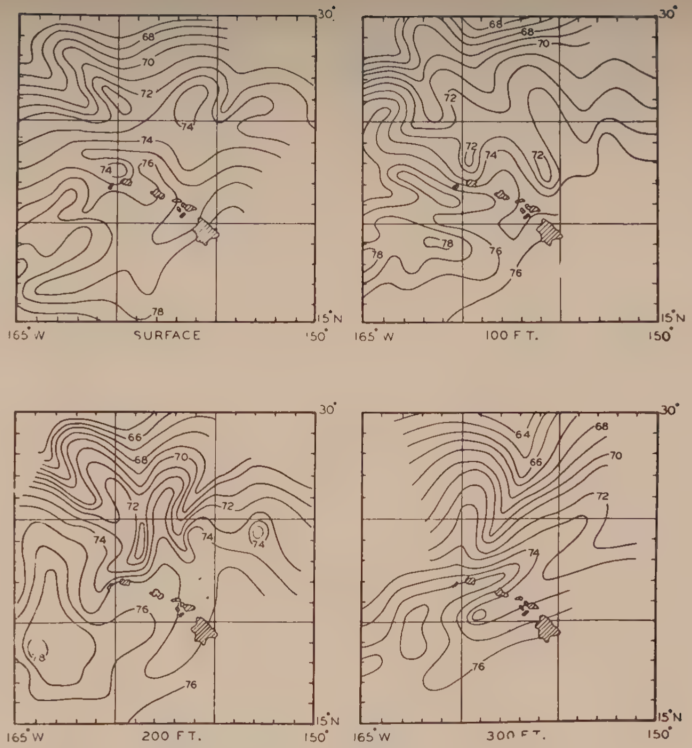

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
64
66
68
70
72
74
76
78

FIG. 3. FEBRUARY, average sea temperatures (° F.) at selected depths (1941–1947).

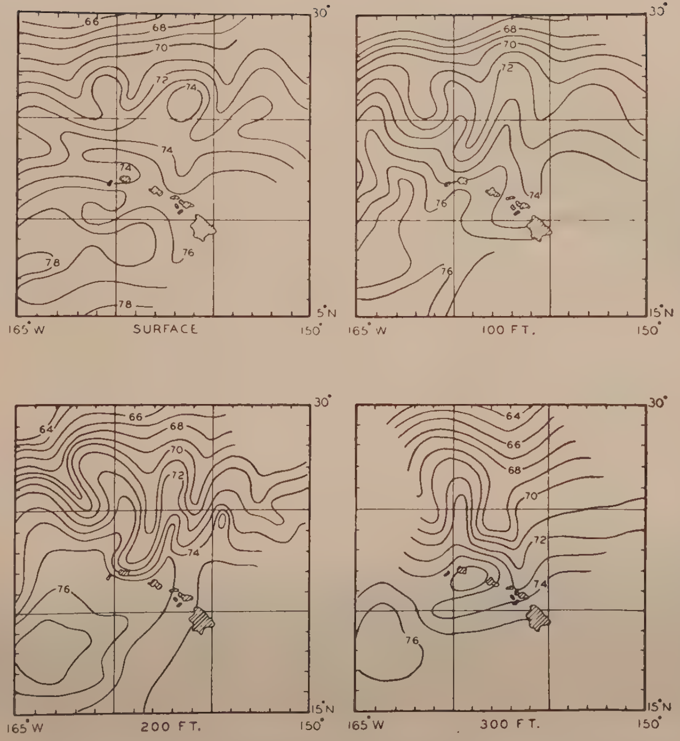

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
64
66
68
70
72
74
76
78

FIG. 4. MARCH, average sea temperatures (° F.) at selected depths (1941–1947).

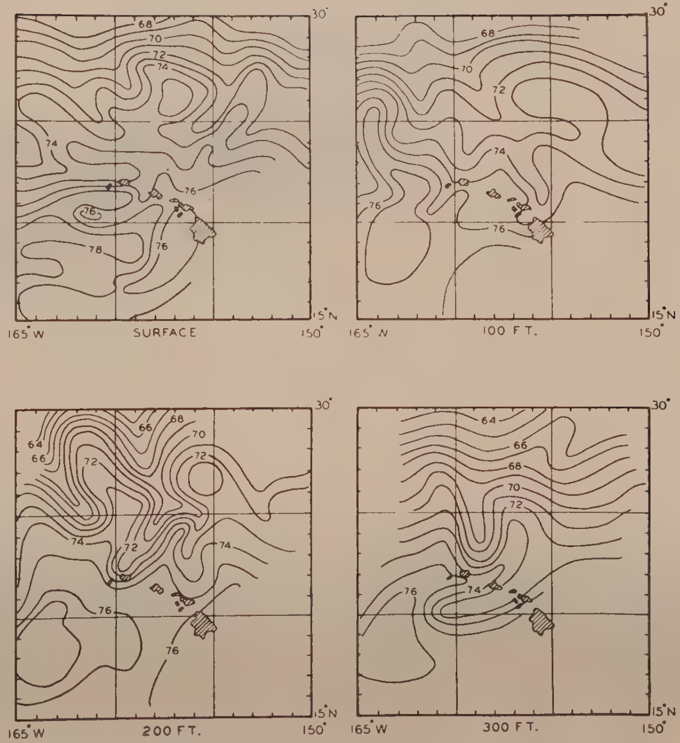

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
64
66
68
70
72
74
76
78

FIG. 5. APRIL, average sea temperatures (° F.) at selected depths (1941–1947).

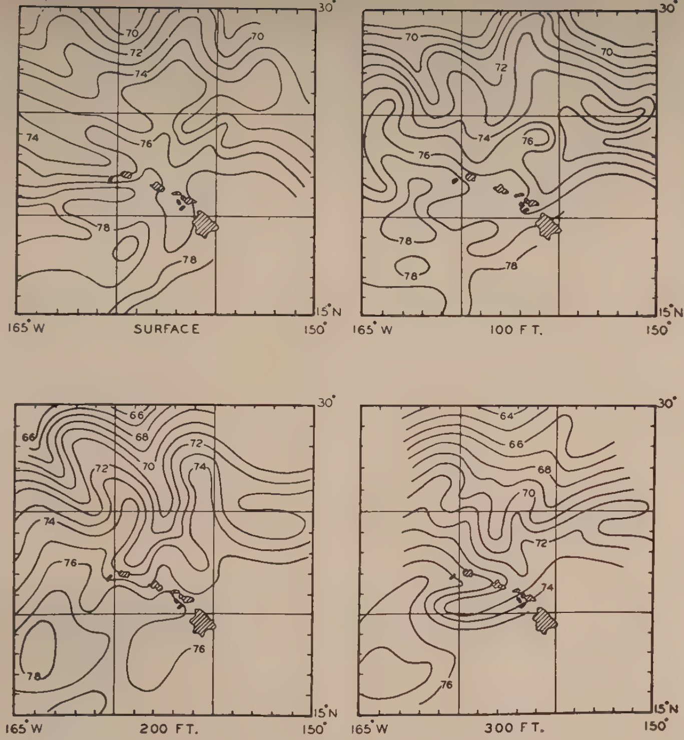

30°
15°N
165° W
SURFACE
150°
100 FT.
200 FT.
300 FT.
64
66
68
70
72
74
76
78

FIG. 6. MAY, average sea temperatures (° F.) at selected depths (1941–1947).

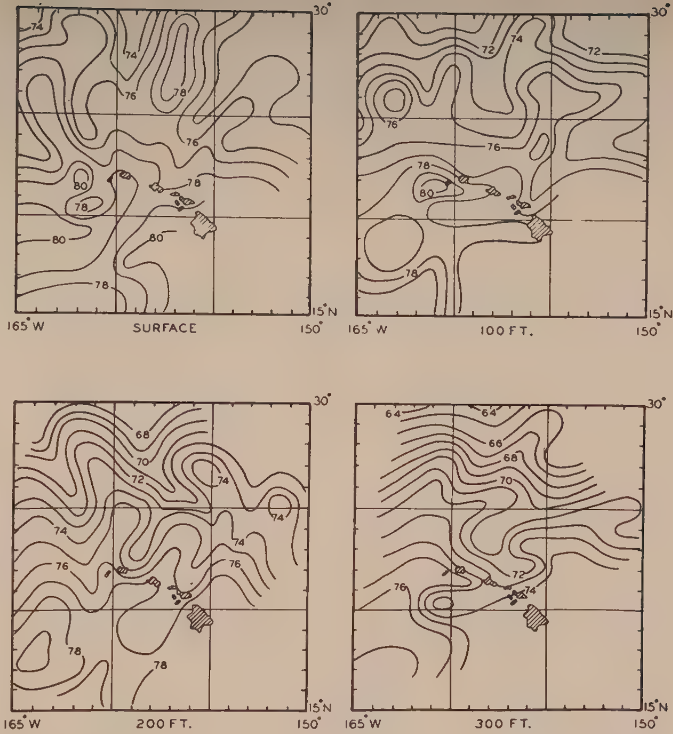

30°
15°N
165° W
SURFACE
150°
100 FT.
200 FT.
300 FT.
64
66
68
70
72
74
76
78
80

FIG. 7. JUNE, average sea temperatures (° F.) at selected depths (1941–1947).

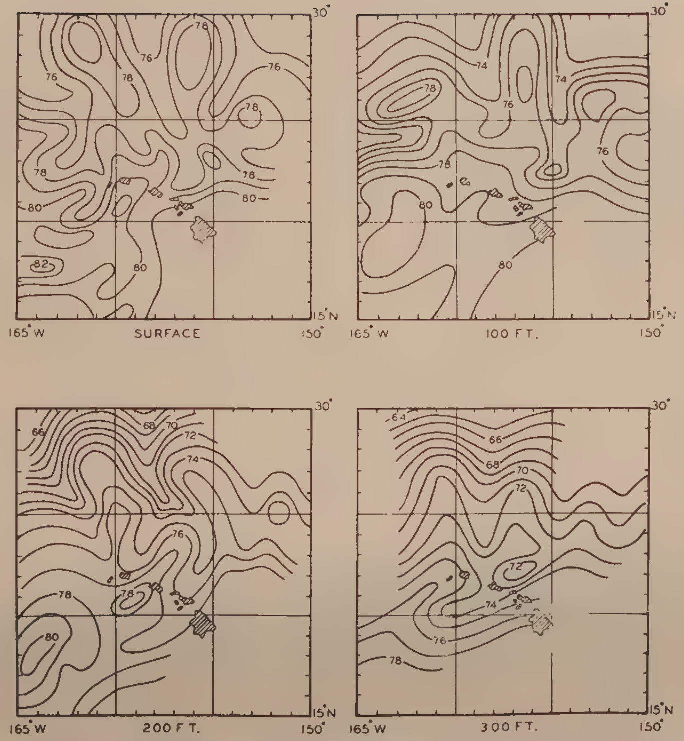

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
64
66
68
70
72
74
76
78
80
82

FIG. 8. JULY, average sea temperatures (° F.) at selected depths (1941–1947).

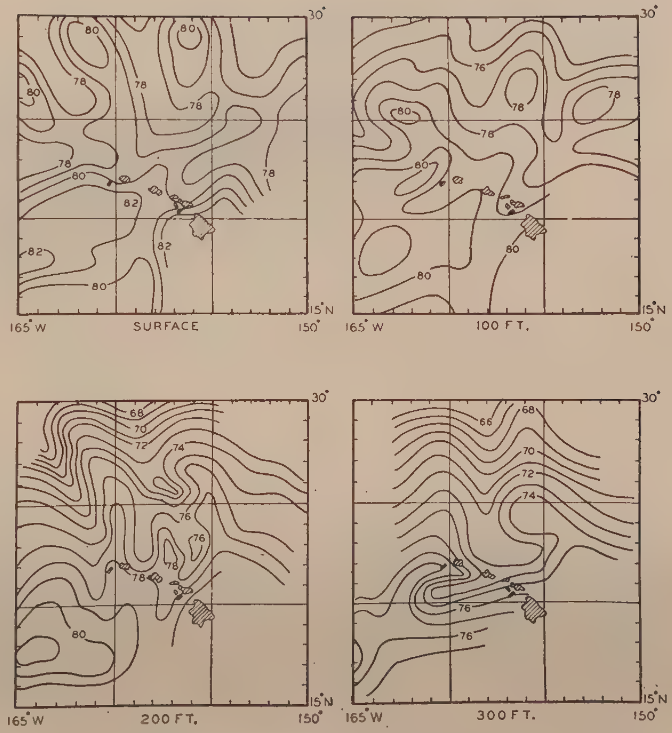

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
66
68
70
72
74
76
78
80
82

FIG. 9. AUGUST, average sea temperatures (° F.) at selected depths (1941–1947).

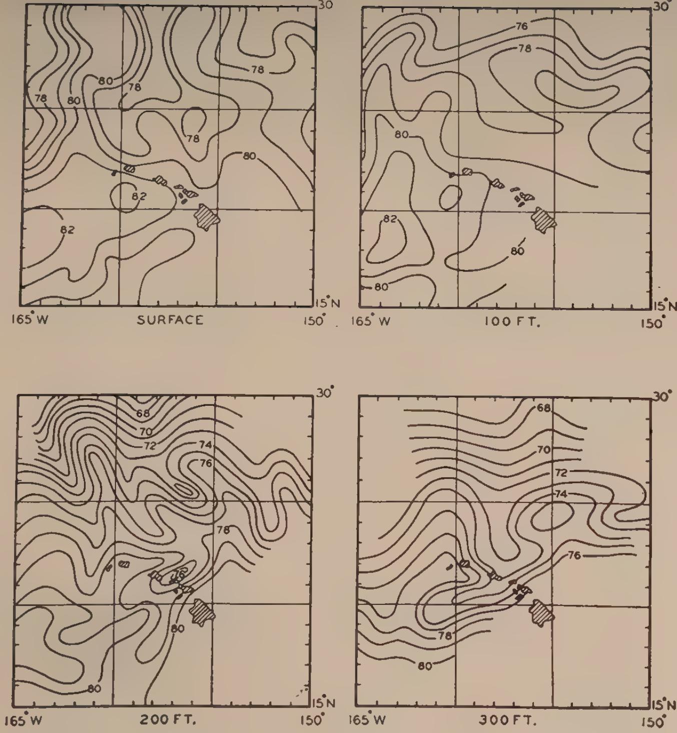

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
68
70
72
74
76
78
80
82

FIG. 10. SEPTEMBER, average sea temperatures (° F.) at selected depths (1941–1947).

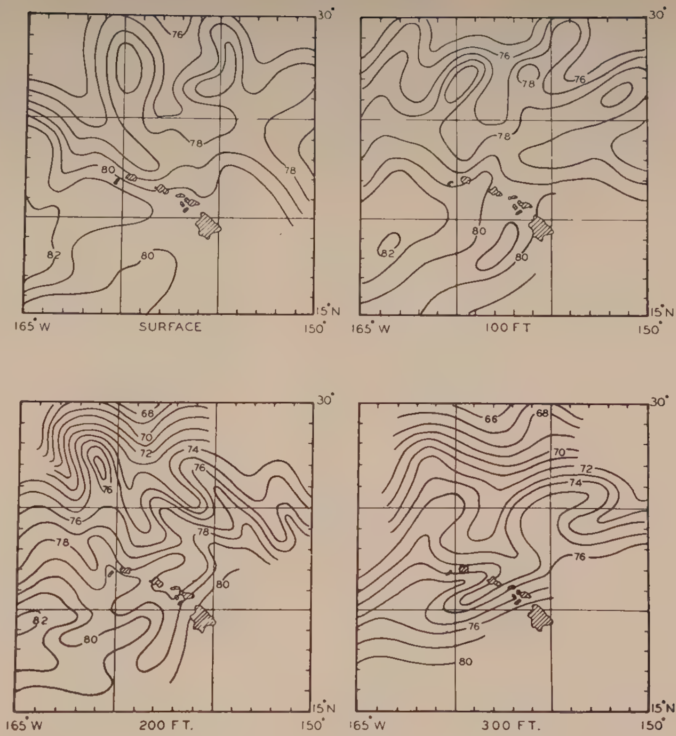

30°
15°N
165° W
150°
SURFACE
100 FT
200 FT.
300 FT.
66
68
70
72
74
76
78
80
82

FIG. 11. OCTOBER, average sea temperatures (° F.) at selected depths (1941–1947).

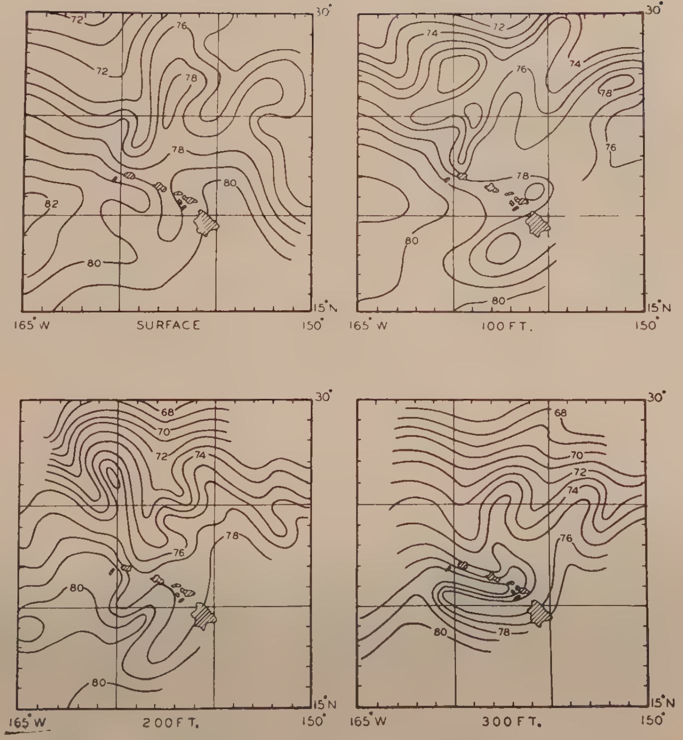

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
66
68
70
72
74
76
78
80
82

FIG. 12. NOVEMBER, average sea temperatures (° F.) at selected depths (1941–1947).

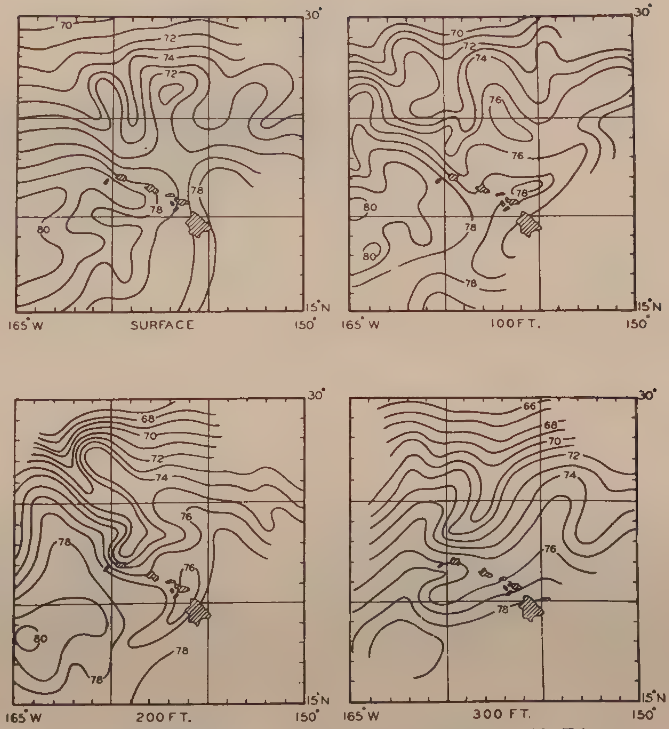

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
66
68
70
72
74
76
78
80

FIG. 13. DECEMBER, average sea temperatures (° F.) at selected depths (1941–1947).

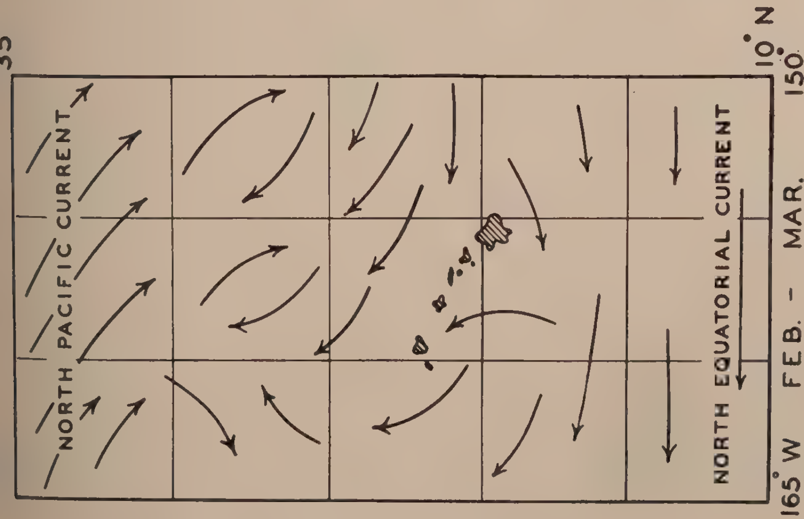

NORTH PACIFIC CURRENT
NORTH EQUATORIAL CURRENT
FEB. - MAR.
165° W
150°
10° N

FIG. 14. Sketch of ocean currents; after Sverdrup.

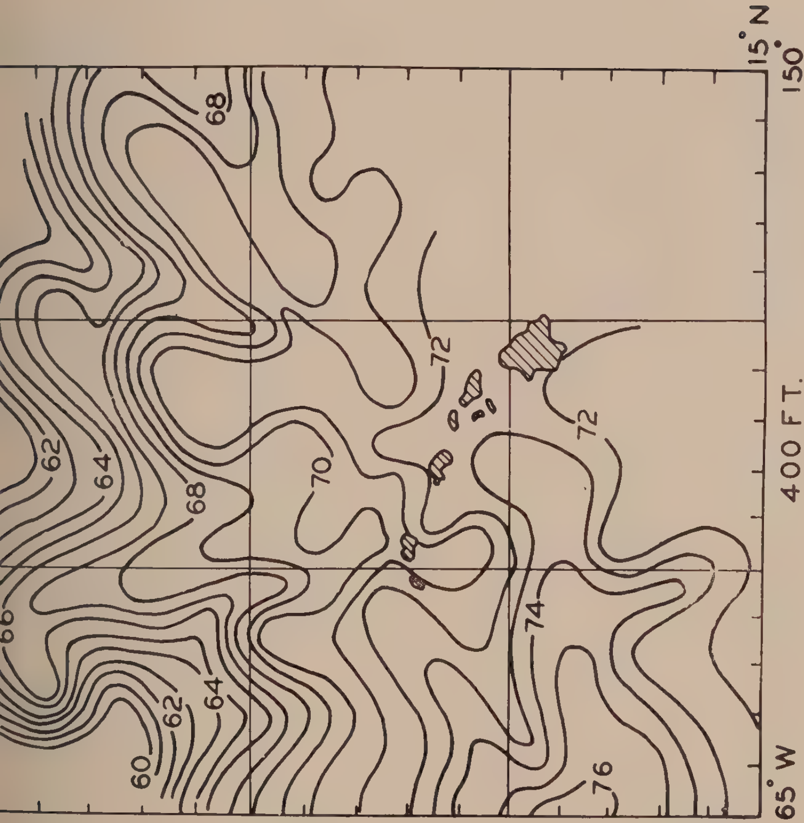

400 FT.
165° W
150°
15° N
60
62
64
66
68
70
72
74
76

FIG. 15. Annual average sea temperatures (° F.) at 400 feet.

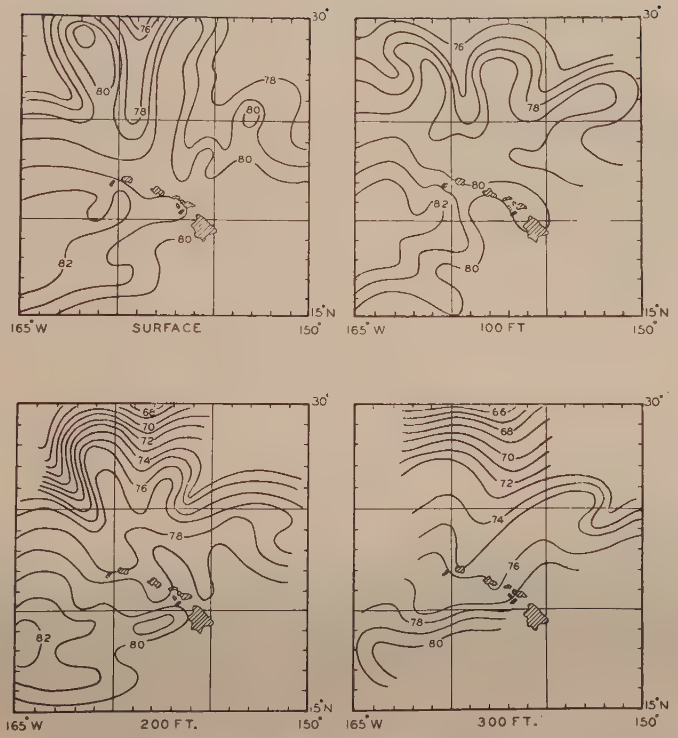

30°
15°N
165° W
150°
SURFACE
100 FT
200 FT.
300 FT.
66
68
70
72
74
76
78
80
82

FIG. 16. Maximum monthly average sea temperatures (° F.), (1941–1947).

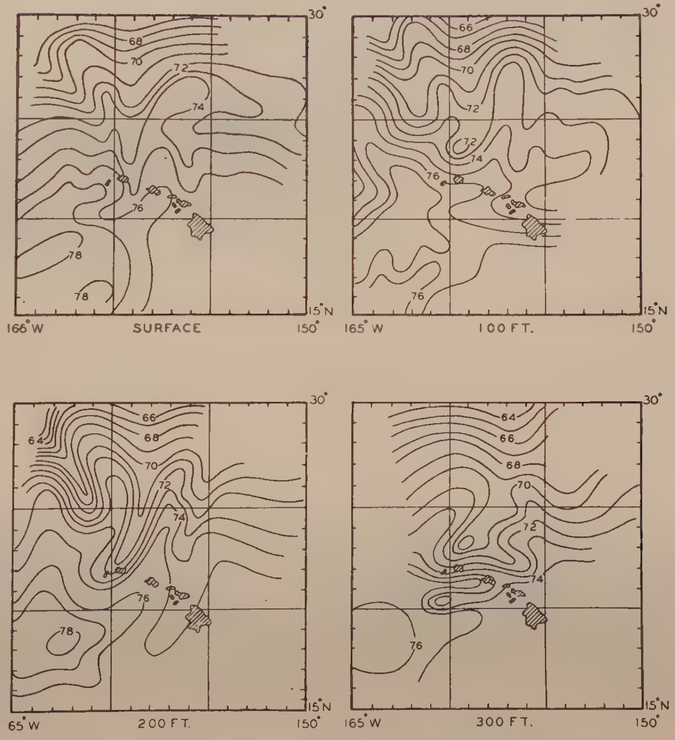

30°
15°N
165° W
150°
SURFACE
100 FT.
200 FT.
300 FT.
64
66
68
70
72
74
76
78

FIG. 17. Minimum monthly average sea temperatures (° F.), (1941–1947).

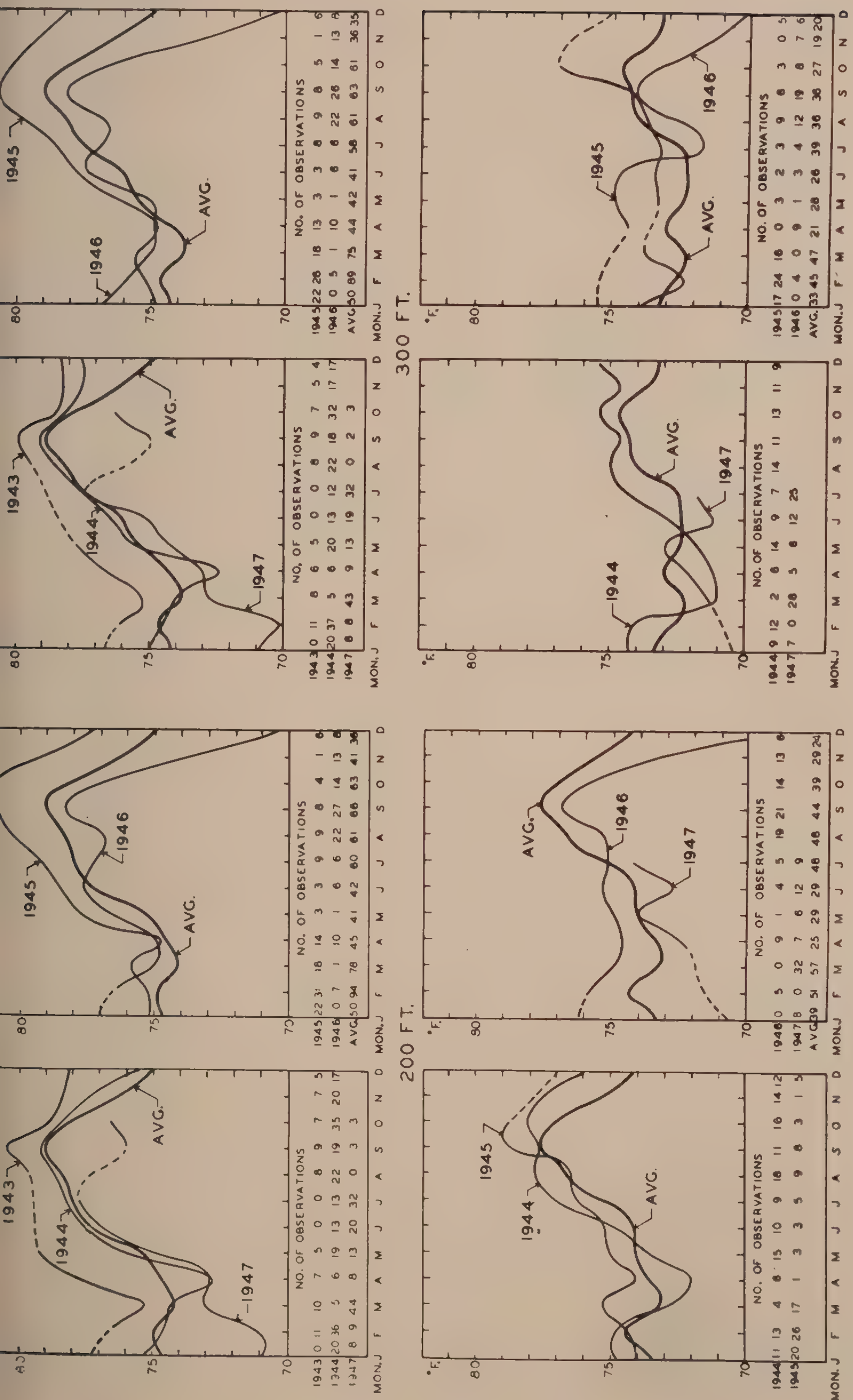
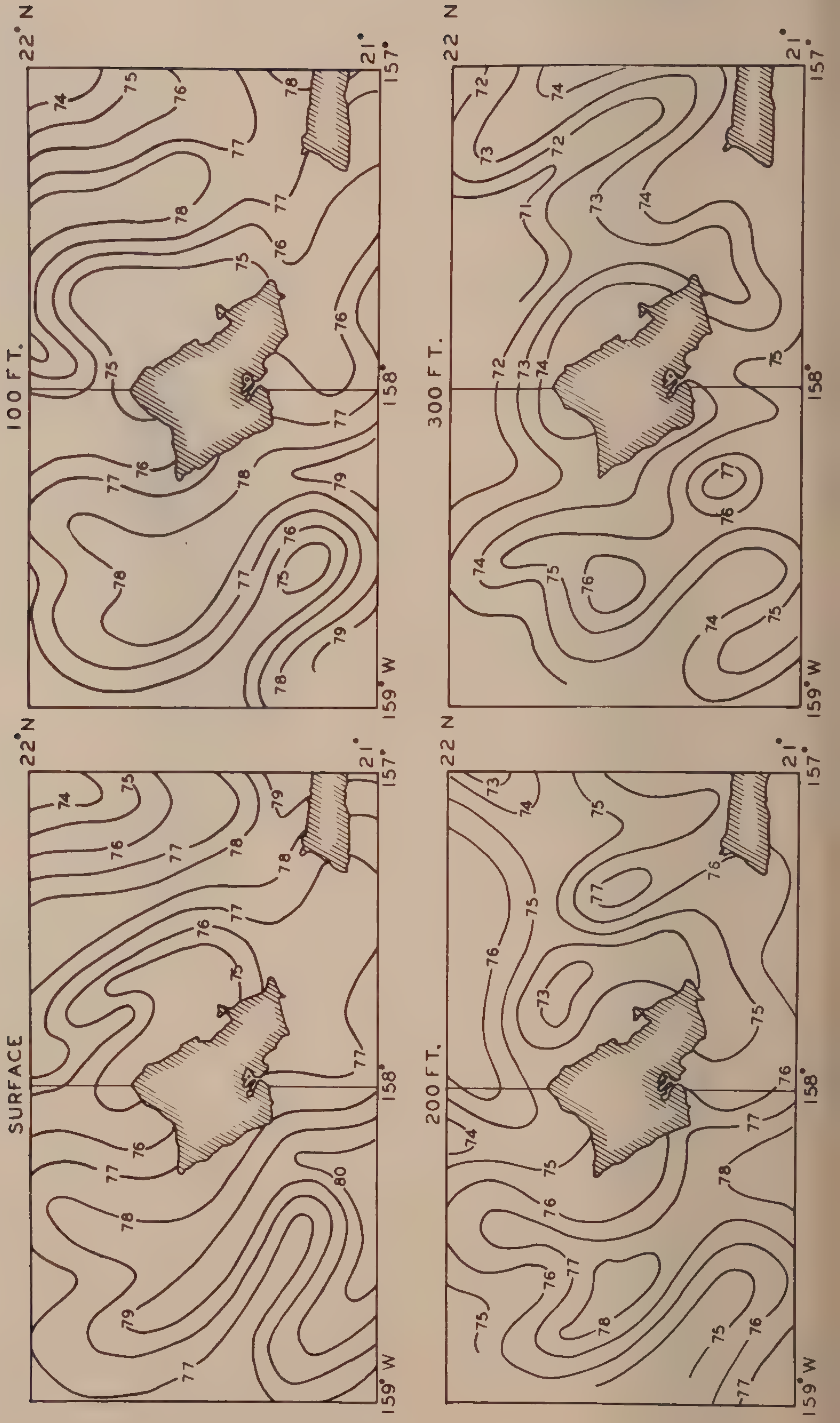
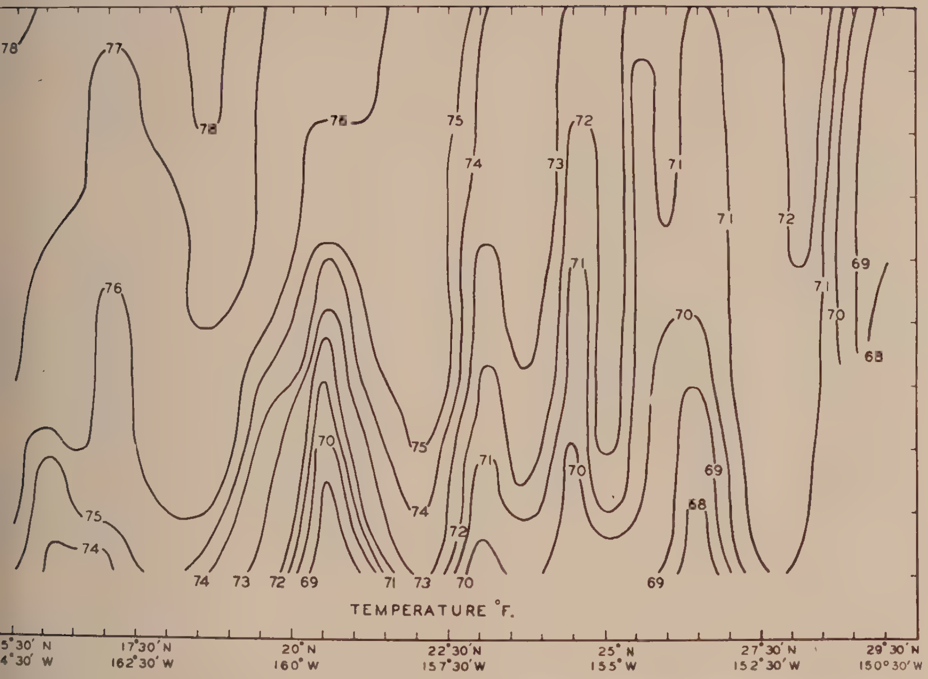
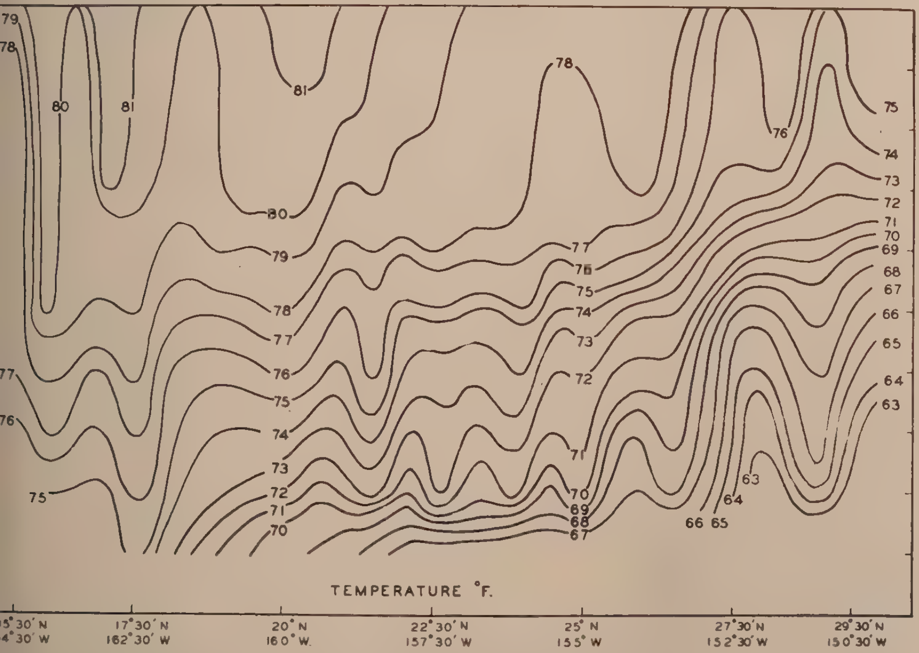


FIG. 18. Annual sea temperature variation (° F.) shown by curves through monthly averages (1943–1947), 20°–25° N, 155°–160° W.


100 FT.
SURFACE
300 FT.
200 FT.
22° N
21°
157°
158°
159° W



. SW–NE sea temperatures (° F.). Cross section (January, February, March, 1941–1947).



. SW–NE sea temperatures (° F.). Cross section (August, September, October, 1941–1947).

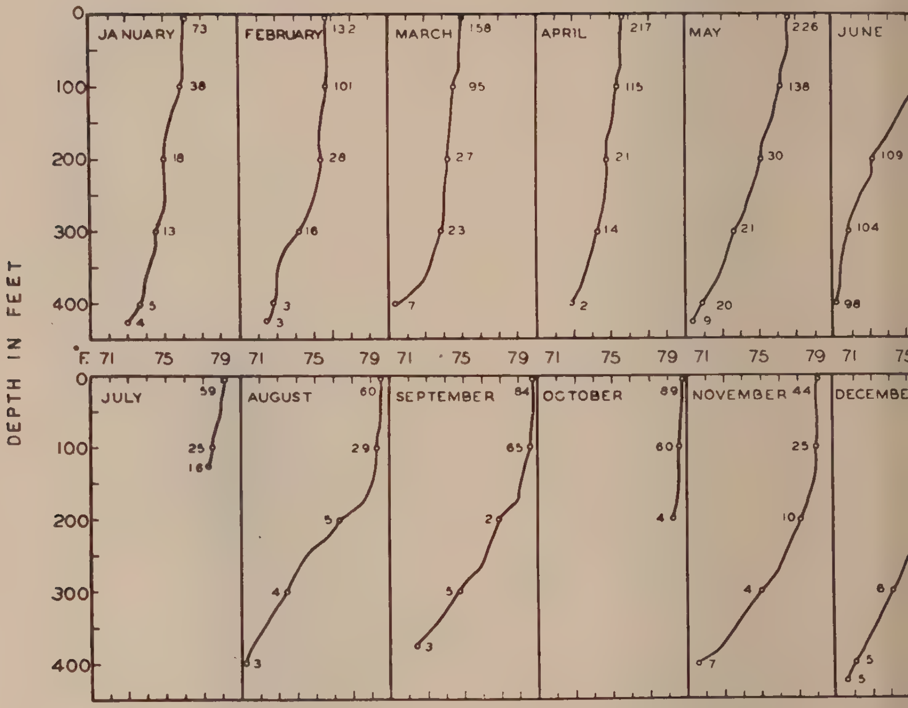


FIG. 22. Temperature depth curves; monthly averages (1941–1947); 20°–25° N, 155°–

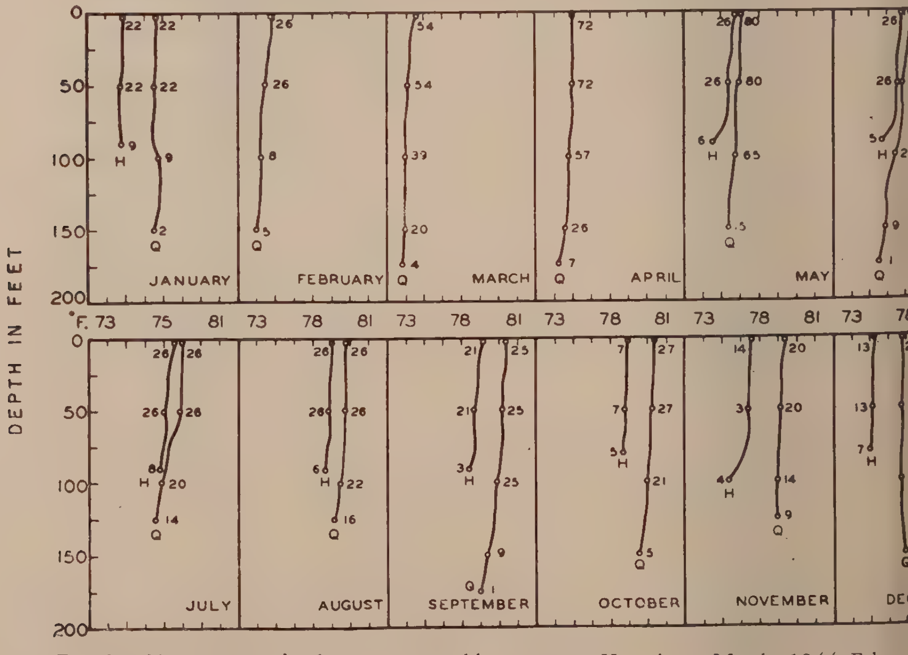


FIG. 23. Temperature depth curves; monthly averages. *H* cruises: March, 1944–Februa
21° 18′ N–157° 53′ W. *Q* cruises: February, 1944–February, 1945; 21° 18′ N–157° 53

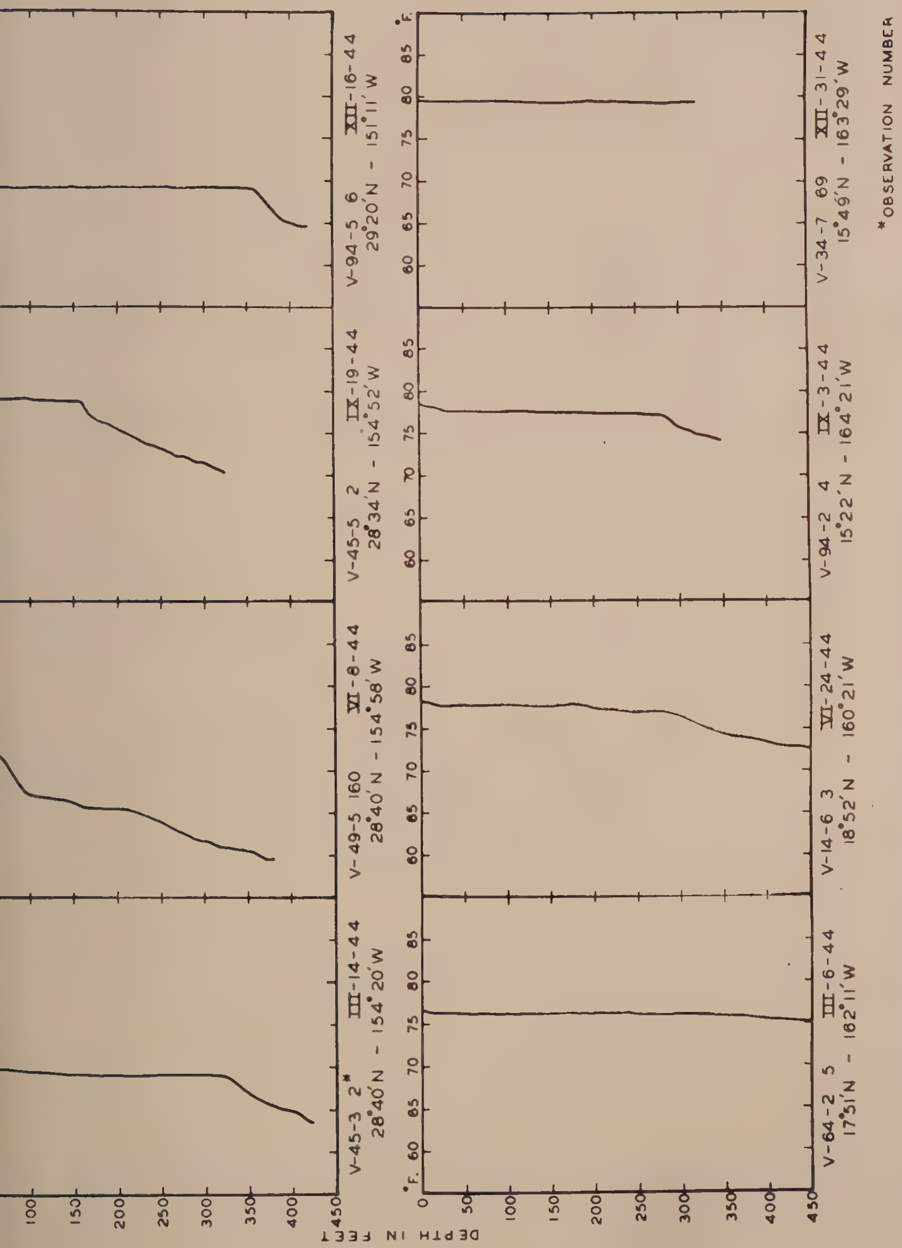


FIG. 24. Typical bathythermograms for March, June, September, December. Upper row, northern portion. Lower row, southern portion.

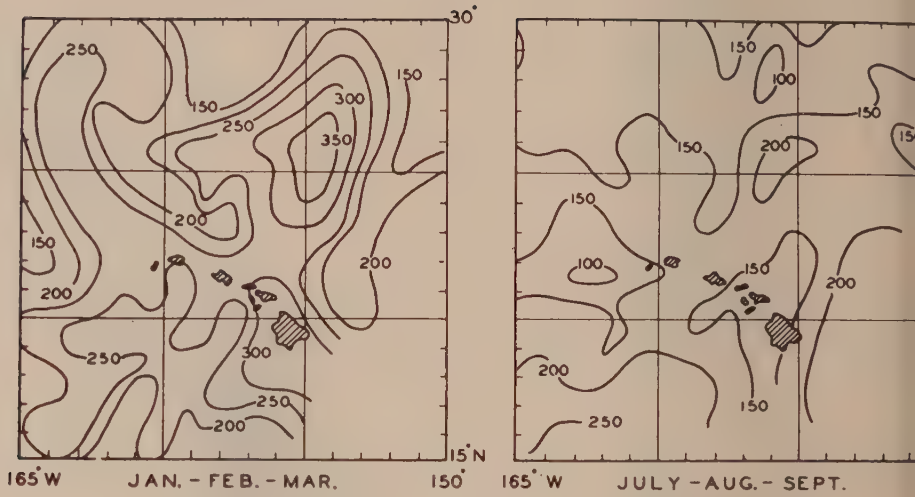

30°
15°N
165°W
150°
165° W
JAN. - FEB. - MAR.
JULY - AUG. - SEPT.
250
150
300
350
200
100

FIG. 25. Average depth of the virtually isothermal layer (1941–1947).

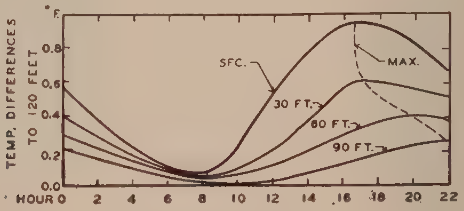
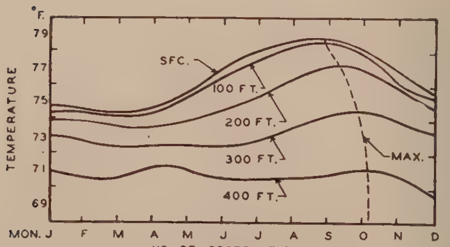


FIG. 26. Diurnal sea temperature variation (° F.); 21°–34° N, 138°–157° W.



NO. OF OBSERVATIONS

	J	F	M	A	M	J	J	A	S	O	N	D
SFC.	50	94	78	45	41	42	60	61	68	63	41	36
100′	50	89	75	44	42	41	58	61	63	61	36	35
200′	39	51	57	25	29	29	48	48	44	38	29	24
300′	33	45	47	21	28	28	39	38	36	27	19	20
400′	15	25	25	6	14	16	18	17	14	15	10	12

FIG. 27. Annual variation of temperature. 20°–25° N, 157°–160° W.

Contribution No. 469

THE RAY-PARTICLE ANALOGY[1, 2]

By

CARL ECKART

Scripps Institution of Oceanography

ABSTRACT

The similarity between the differential equations governing the motion of a particle and the rays in a wave field is recalled. The two become identical if the particle has unit mass and moves under the action of a potential energy $V = -1/c^2$, where c is the phase velocity of the waves.

In shallow water, the phase velocity of surface gravity waves is $c = (gh)^{1/2}$, where h is the water depth. This suggests the possibility of constructing an analogue computer for tracing the rays in regions of complex bottom topography. A relief map would be constructed, whose surface is at a distance beneath a datum plane that is everywhere inversely proportional to the water depth at the corresponding point. If a ball bearing is allowed to roll on this surface, it will trace out one of the rays, provided that simple precautions are observed in starting its motion.

This analogy can also be used for visualizing the rays in a qualitative fashion by merely inspecting a bottom contour map. Certain relatively unknown wave phenomena are shown to be easily deducible in this manner.

INTRODUCTION

Since the time of Hamilton, it has been known that there is a close analogy between the Newtonian motion of a particle and the refraction rays of light or other forms of wave motion. This analogy is quantitative if a suitable definition of the particle's velocity in terms of the index of refraction is used.

Let c be the phase velocity of the waves, u the velocity of the analogue particle. For simplicity, its mass will be taken to be unity. If the subscripts $_1$ and $_2$ refer to media of different characteristics, then Snell's law of refraction involves the index of refraction

$$n = c_2/c_1 = \sin\theta_2/\sin\theta_1\,, \tag{1}$$

where θ_1 and θ_2 are the angles of incidence and refraction.

Our present problem is to determine the forces that must act on the analogue particle in order that its path in space be identical with the ray. If it is not acted on by any force when it is in a homogeneous medium, it will move in a straight line; since the ray is also straight,

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[1] This work has been supported by the Beach Erosion Board, Corps of Engineers, Department of the Army.

[2] Contribution No. 469 from the Scripps Institution of Oceanography.

Reprint from SEARS FOUND. JOURN. MAR. RES.

the problem is trivial. However, the direction must be altered when it passes from one medium to another. If the forces experienced during this transition are normal to the interface, its components of momentum parallel to the interface will be the same in both media. Consequently

$$u_1 \sin \theta_1 = u_2 \sin \theta_2 \, . \tag{2}$$

It remains to arrange matters so that u_1 and u_2 are determined only by the medium. This requires two assumptions: If the particle has a potential energy characteristic only of the medium, the conservation of energy yields

$$\tfrac{1}{2} u_1^2 + V_1 = \tfrac{1}{2} u_2^2 + V_2 = W \, ;$$

if the analogue particle is always given the same total energy, W, then u_1 and u_2 will be characteristic of the medium, as required.

Then Eq. (2) can be written

$$n = u_1/u_2 = \sin \theta_2 / \sin \theta_1 \, .$$

Consequently, the motion of the analogue particle will trace out the ray if its speed u is inversely proportional to the phase velocity c.

In fact, the calculation just given is the pre-Fresnel theory of refraction, and it was used by Newton and others, including Hamilton, for the design of lenses. When Fresnel successfully used the wave theory of light to explain diffraction phenomena, Hamilton noted that both theories were consistent with all experiments on the refraction of light, despite the fact that they postulate different velocities of propagation. No direct measurements of the velocity had been made in any optically dense medium, and all indirect measurements were based on the index of refraction. Thus the transition from the one theory to the other involved only a revision of ideas, and no conflict with observed fact.

His attention having been attracted to the ray-particle analogy, Hamilton examined it for possible application to the dynamics of a particle. This led him to the discovery of the principle of least action, which is basic in modern dynamical theory (Hamilton, 1828–1837; Klein, 1926). It is of interest to note also that Louis de Broglie (1924) retraced this train of thought in the reverse direction and obtained results of the greatest importance for atomic physics.

This analogy between rays and the paths of particles has not been used in the theory of surface gravity waves. Without suggesting that it will be found to have any other significance than an analogy, on which it may be feasible to construct an analogue computer, it seems desirable to examine it in more detail.

THE GENERAL ANALOGY

According to Fermat's principle, the rays (i. e., orthogonals to the surfaces of equal phase) are curves in space along which the point of intersection (phase-point) with the moving phase surface travels with the velocity $c\,(x, y)$. If a ray joins the fixed points A and B in space, the time required for the phase-point to move from A to B is therefore

$$T = \int_A^B ds/c(x, y)\,, \tag{3}$$

where ds is the element of length on the ray. Moreover, for given A, B, and $c\,(x, y)$, T is an extremum (often a minimum) for the ray. That is, all paths of integration that differ only slightly from the ray yield values of T that are either all greater or all less than that for the ray.

Let the equation of the ray be given in the parametric form

$$\begin{aligned} x &= x\,(\tau)\,, \\ y &= y\,(\tau)\,, \end{aligned} \tag{4}$$

where τ is some parameter, which can be specified later in various ways. Then it follows from the above that the differential equations of the ray are

$$\begin{aligned} \frac{d}{d\tau}\left(\frac{1}{uc}\,\frac{dx}{d\tau}\right) - u\,\frac{\partial}{\partial x}\left(\frac{1}{c}\right) &= 0\,, \\ \frac{d}{d\tau}\left(\frac{1}{uc}\,\frac{dy}{d\tau}\right) - u\,\frac{\partial}{\partial y}\left(\frac{1}{c}\right) &= 0\,, \end{aligned} \tag{5}$$

where

$$u^2 = \left(\frac{dx}{d\tau}\right)^2 + \left(\frac{dy}{d\tau}\right)^2. \tag{6}$$

Since the parameter τ is arbitrary, it may be defined by the differential equation

$$u^2\,c^2 = 2\,. \tag{7}$$

With this definition, the parameter τ is measured in units sec cm^{-2}, and Eq. (5) becomes

$$\begin{aligned} \frac{d^2x}{d\tau^2} - \frac{\partial}{\partial x}\left(\frac{1}{c^2}\right) &= 0\,, \\ \frac{d^2y}{d\tau^2} - \frac{\partial}{\partial y}\left(\frac{1}{c^2}\right) &= 0\,. \end{aligned} \tag{8}$$

These are quite analogous to those for a particle of unit mass moving under the action of the potential energy

$$V = -1/c^2 . \tag{9}$$

The total energy of the particle is therefore

$$W = \tfrac{1}{2}u^2 - 1/c^2 . \tag{10}$$

There are two minor exceptions to this analogy. 1) The independent variable is the parameter τ and not the physical time, and consequently the time (in τ-units) required by the analogue particle to move along the ray from A to B will not be given by Eq. (3). This corresponds to the fact that a measurement of the velocity of light would have decided between the two theories. 2) Because of Eq. (7), $u = \sqrt{2}/c$ and hence the total energy of the analogue particle must be zero and therefore cannot have arbitrary values. This corresponds to the fact pointed out in the Introduction that it was necessary to suppose that the analogue particle is always started with the same total energy.

THE FEASIBILITY OF AN ANALOGUE COMPUTER

The phase velocity c of surface gravity waves varies with the depth of water and with the period. For a given period the contours of equal velocity thus coincide with those of equal depth. Imagine a relief map constructed so that its depth below a horizontal datum plane is not water depth but rather (to some suitable scale) $1/gc^2$, where g is the acceleration of gravity. Further, imagine a particle of unit mass that is capable of sliding on this surface without friction and that is launched from rest by sliding down a frictionless trough from the datum level to a point on the surface. After the particle leaves the trough its motion will be governed by Eq. (7) and (8), and therefore it will trace the ray. It should be noted that, in this model, τ becomes the physical time and that time t of the wave theory does not appear.

Such a frictionless sliding particle may be approximated by a rolling sphere, provided its radius is so small that its rotational kinetic energy is negligible compared to its translational kinetic energy. The feasibility of using small ball-bearings for this purpose has been established in connection with analogue computers in other fields.

However, there are other difficulties. Because of the dispersion of deep water waves, it seems necessary to construct one relief map for each wave period to be studied; this might be overcome by tracing the rays graphically in those regions where the water is not so deep that refraction is negligible nor yet so shallow that the dependence of c on wave period is negligible. It would then be necessary to construct only one relief map for the shallow water regions, where refraction is most marked and most difficult to determine by graphical methods.

In shallow water,

$$c^2 = gh\,,$$

where h is the water depth. Hence the ordinate of the relief map would be inversely proportional to the water depth. As the beach is approached, the map would have an ever increasing slope and the particle would leave the surface and fall freely through the air before the "water's edge" was reached. It is possible that a proper choice of design parameters can minimize the effect of this error until it is negligible as compared with other errors arising from the neglect of phenomena occurring in the surf zone.

Even if the physical construction of such analogue computers is not feasible, the analogy may still be used in visualizing the effect of bottom topography on the propagation of waves. For example, a submarine canyon will be represented on the relief map by a spur-like ridge pointing toward the shore. The action of the ridge in deflecting the analogue particles away from those parts of the beach close to the canyonhead will be obvious immediately. Also, the course of rays entering a harbor through a narrow channel can be easily visualized. In the analogue, the underwater ridge extending seaward from a promontory becomes a trough that guides the analogue particles so that they can hardly avoid striking the beach near its most seaward point.

Furthermore less well known phenomena can be readily visualized. Thus the shoal water over a bar would be represented by a depression on the relief map. Immediately it becomes clear that the analogue particle, if it enters the depression in a suitable manner, may execute several oscillations before escaping or may even describe a path that intersects itself several times. Furthermore, it becomes apparent that waves generated in shoal water, if they approach a continental shelf at a steep angle, may be totally reflected from the deep water regions (i. e., from the higher regions of the analogue relief-map). These effects, and the limitations of ray theory in dealing with them, are being discussed elsewhere.

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Contribution No. 470

sactions, American Geophysical Union Volume 31, Number 4 August 1950

REFRACTION OF SHALLOW WATER WAVES: THE COMBINED EFFECT OF CURRENTS AND UNDERWATER TOPOGRAPHY

(Contribution from the Scripps Institution of Oceanography, New Series, No. 470)

Robert S. Arthur

Abstract--A solution is given for determining the refraction effect according to Fermat's Principle for the case of shallow water waves moving in any given distribution of current and depth. Application is made to an analytic model of an intense rip current, and the results are compared to actual rips.

Introduction--UNNA [1942] and SVERDRUP [1944] have considered the case of deep water waves ting a following or opposing current, and JOHNSON [1947] has discussed the refraction of deep- r waves encountering a uniform current which moves at an angle to the wave direction. In the ent paper the combined refraction effect of underwater topography and of a current is discussed he special case of shallow water waves whose velocity, c, is given to a satisfactory approxima- by the expression

$$c^2 = gh \quad \dots\dots (1)$$

e g is the acceleration of gravity and h is the depth. Horizontal variations in current and depth rise to a refraction problem involving a moving medium and a relative wave velocity which es horizontally. The problem is analogous to that of determining the minimal flight path of an lane flying in a variable wind field. A solution to the minimal flight problem is used to deter- e the refraction effect of a current distribution of the type represented by rip currents. The od is also applicable to tide rips and longshore currents in shallow water, and the former, icularly, may be expected to show refraction effects of importance [JOHNSON, 1947].

The close correspondence between certain problems of minimal flight and refraction was noted RANK [1918]. The determination of the minimal flight path in two dimensions for a fixed air d was first accomplished by ZERMELO [1931]. His results were subsequently extended, and MIRA FERNANDES [1932] has obtained the solution for an air speed which varies in space and . ARROW [1949] includes a review of the literature in his recent paper.

Solution--Diagrams which show the refraction effect of bottom topography have proven useful e study of waves and related phenomena in the nearshore zone [MUNK and TRAYLOR, 1947]. s been customary on such diagrams to draw a network of lines which are perpendicular to the ts and are, therefore, designated as orthogonals. The orthogonals correspond to the rays in al refraction, and according to Fermat's Principle, they represent paths of least time. It is, , Fermat's Principle which is the basis for the analogy between the refraction and minimal t path problems. In our problem the direction of wave propagation and wave speed relative to urrent correspond to the heading and air speed, respectively, of the aircraft. The current esponds to the wind field, and the ray path corresponds to the minimal flight path. Since the are not perpendicular to the wave crests in the presence of a current, the term "orthogonal" longer appropriate.

The refraction problem is next formulated mathematically. We consider the two-dimensional and let the rectangular coordinates of a moving point on a ray be given as functions of the time, at is $x = x(t)$ and $y = y(t)$. Let the x- and y-components of the horizontal component of the current city, v_H, be v_x and v_y respectively, and let θ designate the angle between the relative wave city, c, and the positive x-direction. Then $x = x(t)$ and $y = y(t)$ must satisfy

$$\left.\begin{aligned} dx/dt &= v_x + c \cos\theta \\ dy/dt &= v_y + c \sin\theta \end{aligned}\right\} \quad \dots\dots (2)$$

rding to Fermat's Principle, the ray between two points P_1 and P_2 (see Fig. 1) is the path of travel time, subject to (2) which relate the variables.

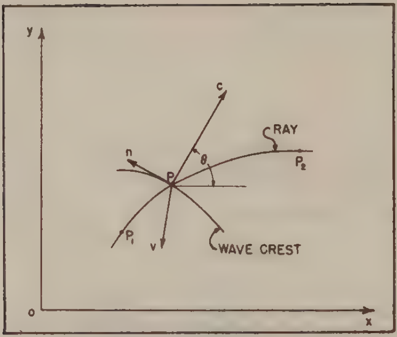


Fig. 1--Schematic diagram showing ray, wave crest, and velocity vectors

This formulation of the problem is identic
mathematically with that for the determination
the flight path of least time for the airplane.
ZERMELO'S [1931] result gives as the conditio
to be satisfied for the minimal path

$$d\theta/dt = -(\partial v_x/\partial y)\cos^2\theta + (\partial v_x/\partial x -$$

$$\partial v_y/\partial y)\cos\theta\sin\theta + (\partial v_y/\partial x)\sin^2\theta \;. \;.($$

where the assumption is made that c is constan
(uniform depth) and that $c^2 > v_H^2$. If v_c denote
the component of v_H in the direction of c, (3) ha
the form

$$d\theta/dt = -(\partial v_c/\partial y)\cos\theta + (\partial v_c/\partial x)\sin\theta \;. \;.(3$$

The assumption that c is constant is gener
not appropriate in wave refraction applications. Zermelo's result is easily generalized for the
where c is a function of x and y and the result is [DE MIRA FERNANDES, 1932]

$$d\theta/dt = -[\partial(v_c + c)/\partial y]\cos\theta + [\partial(v_c + c)/\partial x]\sin\theta \;\ldots\ldots\ldots\ldots$$

If n denotes the direction of the tangent to the wave crest (see Fig. 1), (4) takes the simple form

$$d\theta/dt = -\,\partial(v_c + c)/\partial n \;\ldots\ldots\ldots\ldots\ldots\ldots($$

Condition (4′) can be stated as follows:

> The rate of change of wave direction is numerically equal to the variation or shear along the crest in a scalar field composed of the relative wave speed and the current component in a direction normal to the crest; the direction of wave advance turns toward the direction of negative shear along the crest.

Equations (2) and (4) form a system of three ordinary differential equations with three depe
variables x = x(t), y = y(t), and θ = θ(t). Since the equations are first order, a solution for any
sired ray and the crest orientation along the ray can always be obtained, although numerical me
may be necessary. The problem of determining the refraction effect is thereby solved, and adva
tageously, since the rays are determined directly. A graphical method of solution similar to tha
given by JOHNSON, O'BRIEN, and ISAACS [1948] for refraction by bottom topography alone can
applied to the equivalent system consisting of (2) and (4′).

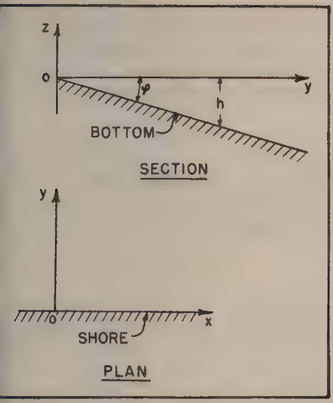
Application--The method of solution as outlined is applied to obtain the wave refraction effe
of a current distribution of a type represented by rip currents, which are narrow, fast flowing c
rents directed away from shore. The method permits the use of an actual rip current distributi
but no detailed observations of such a distribution are available. However, observations of the
pattern and the velocities in the "feeders" and "neck" are available [SHEPARD, EMERY, and I
FOND, 1941; SHEPARD and INMAN, 1950], and these have been used as a guide in choosing an a
lytic representation.

The bottom is assumed to have a uniform slope of 1:50, and the coordinate axes are as show
(see Fig. 2). The assumed x- and y-components of the current are

$$\left.\begin{aligned} v_x &= -3.60[2 - (y/250)^2]\cdot F(y/250)\cdot\int_0^{x/25} F(\alpha)d\alpha \\ v_y &= 0.1442y\cdot F(y/250)\cdot F(x/25) \end{aligned}\right\}\;\ldots\ldots\ldots\ldots$$

where the length and time units are feet and seconds, respectively, and where the function F is
fined by

$$F(\alpha) = (1/\sqrt{2\pi})\,e^{-\alpha^2/2}$$



g. 2--Coordinate axes for example

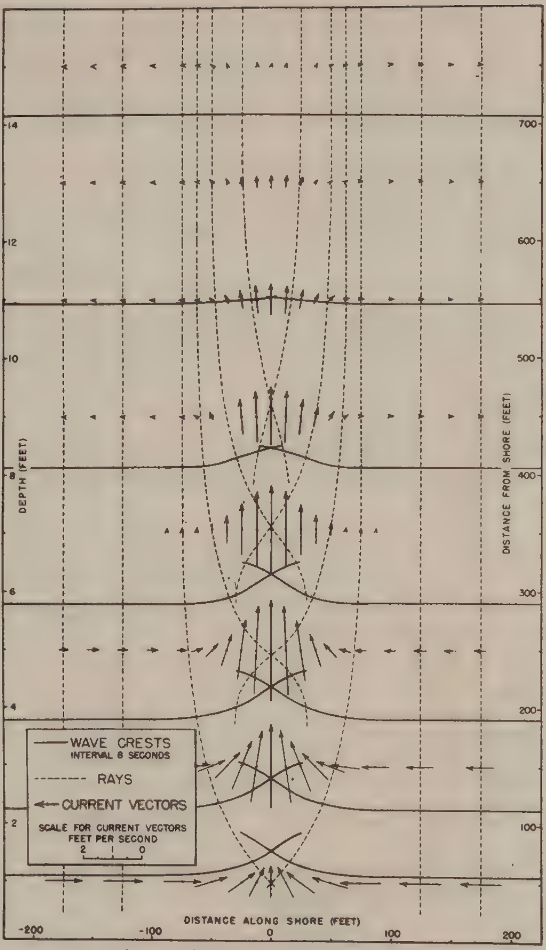


Fig. 3--Diagram showing computed results of refraction by both currents and underwater topography

tions (5) have been chosen to satisfy ntinuity relationship and to give a ent distribution of a type represen- ed by rip currents (current vectors, 3, are derived from (5)). The max- n value of the current is 3.5 ft/sec width of the neck in which the out- l flow is appreciable is 100 ft (see 3). If the equation of continuity $/\partial x) + (\partial v_y/\partial y) + (\partial v_z/\partial z) = 0$ is grated from surface to bottom and oundary condition that the normal city be zero at surface and bottom plied, the resulting form is

$${}_x/\partial x + \partial v_y/\partial y = - v_y/y \quad . . . . . . (6)$$

e it has been assumed that v_x and re uniform with depth. Equations atisfy (6).

Several rays (dashed lines, Fig. 3) been constructed by solving (2) (4) numerically, with the initial con- n that the rays be normal to shore depth of 15 ft. Values of $\theta(t)$ have used in constructing segments of the wave crests along the rays at intervals of eight seconds. crests (solid lines, Fig. 3) have been completed by interpolation. The solid lines shown can terpreted to be either successive positions of the same crest at intervals of eight seconds or e the wave period is constant, the position of the wave crests at a fixed time in a train of waves riod eight seconds. The free ends of the crests are in the proximity of caustics, and the so- n has not been continued through these regions because refraction principles alone are inade- e for determination of the wave features under these circumstances. Ordinarily the width of urrent at the neck is not large compared to a wave length and the additional complication of e diffraction may also modify the solution.

Waves in actual rip currents in some cases show features which are similar to those in the trated refraction pattern. The crests generally show a lag in the neck of the current and the scross pattern of crests may sometimes be seen in very shallow water. The current velocities velocity gradients chosen for the model are typical only of the strongest rip currents. Many seem to cause only a gentle retardation of the wave crests with no apparent crisscross pat- ; this difference may be the result of much lower current velocities and velocity gradients. her factor is the channel which results from erosion of a sand bottom below the currents in eeders and neck. The effect on wave velocity of the greater depth in the channel tends to offset effect of current shear in refracting the waves.

Quantitative deductions regarding wave energy and height are not attempted in the exa
As the rays proceed toward shore, divergence occurs first, followed by convergence near t
caustics. There is evidence that simple height considerations based on the conservation o
between rays do not hold for breaking waves in the presence of currents [CARR, 1949]. Re
and diffraction become important, and observations show lower waves inside the neck of r
outside [SHEPARD, EMERY, and LAFOND, 1941].

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writer's attention by one of Arrow's co-workers, George E. Forsythe.

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Contribution No. 471

ON THE ORIGIN OF INTERNAL TIDE WAVES IN THE OPEN SEA[1,2]

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ABSTRACT

Several mechanisms are examined which might explain the observed preponderance of internal waves of tidal period. It is concluded that the effect of the earth's rotation on the velocity of internal waves is an important factor in favoring the generation of such internal waves.

The phenomenon of internal waves with periods of the tide generating forces, designated briefly as internal tides, occurs not only in shallow seas and straits but in the open ocean as well. The amplitude of these internal tides and the water transport connected with them are much larger than those of the normal surface tides. These internal tides exert a much greater influence on the thermohaline structure of the oceans than do normal tides. Fr. Nansen and Bj. Helland-Hansen were the first to notice the existence of such internal waves, but Otto Pettersson was the first to associate these large periodic displacements of water masses with the tide generating forces. Such internal tides have been observed during all subsequent oceanographic expeditions where anchor stations were made in deep water. The anchor stations of the METEOR in the North and South Atlantic oceans have been discussed in the METEOR publications, and those of the SNELLIUS Expedition have been elaborated by Dr. Lek. The later cruises of the METEOR (1937, 1938) in the North Atlantic and in the area between the Cape Verde and Canary islands, the observations of the ALTAIR at anchor stations in the mean current of the Gulf Stream north of the Azores, the many cruises of the ATLANTIS in the western North Atlantic, the observations of the DANA Expedition, etc., *all* have shown that internal tides are as common as tides at the surface of the ocean.

Recent observations, taken on the Marine Life Research cruises of the Scripps Institution of Oceanography, have shown again very definitely that the influence of internal tides is great in this area also. This influence can be very disconcerting when attempting to obtain

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[1] Contribution from the Scripps Institution of Oceanography, New Series, No. 471.

[2] I should like to draw attention to a paper by Haurwitz (1950) which appeared while this paper was in press. The conclusions reached in Haurwitz' paper are similar to the ones presented here.

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the mean distribution of oceanographic elements, and therefore knowledge of the behavior of internal tides is required in order to eliminate their influence (Defant, 1950). However, aside from a practical application, the rising and sinking of immense water masses is in itself one of the interesting phenomena of dynamic oceanography; in fact, it is every bit as interesting as normal tides at the surface.

By theoretical and experimental research we are well informed concerning the physical nature of internal waves. Early theoretical models treated two-layered bodies of water with a physical discontinuity between them. Later the problem of internal waves of tidal periods in water masses of continuous density variations with depth were studied, especially by Fjeldstad (1933) and Groen (1948).

Although we know what internal waves with tidal periods are, there still are many difficulties on how such internal waves with large amplitudes develop and why they are so frequent, i. e., why they occur everywhere and at all times. Although observations at anchor stations, up to the present time, do not give accurate data about the velocity of internal tides in the open ocean, they do show clearly and distinctly that internal tides are related to tides at the surface. But the form of this coupling is not the same everywhere, though it seems to remain fixed with time at a fixed locality. This coupling leads to the assumption that internal tides are *forced* waves. If that is so, then they travel with a velocity about 100 times that of the theoretical velocity of *free* internal waves.

Free internal waves with tide periods, once they are generated, will soon lose every connection with the tide at the surface, and the coupling between the two wave systems would vary with time and distance. Since the generation of internal waves requires but little energy, the internal tides generated at different points would spread freely in all directions, the result being a chaos of internal tides in the ocean and the impossibility of finding a suitable method of eliminating their influence. But this is not the case, for internal tides are very regular and are strictly coupled to normal tides at the surface. With the latter they form a well determinated wave system. This has been shown clearly by the observations of the Marine Life Research program

In work with the METEOR data I have already dealt with the question of the generation of internal tides, but at that time it was not possible to give a satisfactory answer. Now, in connection with the Marine Life Research observations, I have been occupied again with this problem, and I would like to submit a few points of view which might make this question clearer. In the following discussion I will work mostly with a model of two superposed water bodies.

In the case of tidal waves in deep water, the entire water masses will be moved with the same periodic tidal velocity; there will be no change of current with depth. If the lower water mass lies on a rough bottom, friction will decrease the intensity of tidal currents and will change the phase of these currents. This influence makes itself felt up to a certain height above the bottom, this height depending on the turbulence of the tidal current. If the lower water mass is not too deep, as on an ocean shelf, then the friction will influence the total underlayer to some extent. On the boundary, shearing stresses will occur which can force a dislocation of the boundary layer. These will produce internal waves or, if they are already present, they will affect amplitude.

The theoretical solution, given previously in the METEOR work (Defant, 1932), is

$$\frac{\zeta_2}{\zeta_1} = 1 - \frac{1}{(h_2/h_1)\, M + 1}, \tag{1}$$

where h_1 designates the height of the upper homogeneous water mass and ρ_1 its density; the corresponding values for the bottom layer are h_2 and ρ_2; $\Delta\rho$ is $(\rho_2 - \rho_1)/\rho$; ζ_1 and ζ_2 are the displacements of the surface and of the boundary; at most they are the amplitudes of the corresponding waves. The function M is given by

$$M = 1 - \frac{tgh(1 + i)\beta_2 h_2}{(1 + i)\beta_2 h_2},$$

where $\beta_2 = \sqrt{\sigma/2\nu_2}$, and ν_2 is the eddy viscosity of the lower layer. Since M is always slightly less than 1, ζ_1 is larger than ζ_2. Therefore this process is incapable of increasing the amplitude of internal waves of tidal character.

A second point of view may be illustrated by the following problem. Let the upper water mass move with constant velocity U_1, the lower with the constant velocity U_2, both parallel to the undisturbed discontinuity layer. A tide generating force,

$$X = f\, e^{i(\sigma t - \kappa x)}, \tag{2}$$

acting in a horizontal direction on the whole system, will produce tide waves at the surface and on the discontinuity layer. The frequency is denoted by σ, the wave number by κ; the velocity of propagation $c = \sigma/\kappa$ is determined by the force. Under which conditions then will real internal waves, whose amplitudes are much larger than the amplitudes at the surface, be generated?

The solution is not difficult to find, since the vertical motion in both layers can be neglected, according to the first approximation in tide theory. In the equations for the amplitudes of the surface and of the boundary layer, the expression

$$c(c-U_1)[(c-U_2)^2\omega_1\omega_2+(c-U_1)^2\rho_1/\rho_2]-[(c-U_2)^2\omega_1+(c-U_1)^2\omega_2\rho_1/\rho_2 \\ +c(c-U_1)\omega_1\Delta\rho].g/k+\Delta\rho g^2/k^2 = D_1 \quad (3)$$

always appears as denominator, wherein $\omega_1 = ctgh\,\kappa h_1$ and $\omega_2 = ctgh\,\kappa h_2$. But this expression, when set equal to zero, is the equation which determines the velocity of the *free* waves of the system. For $U_1 = U_2 = 0$ this equation becomes the well known equation of the velocity of free waves with the wave number κ:

$$c^4(\omega_1\omega_2+\varphi_1/\rho_2)-c^2(\omega_1+\omega_2)g/\kappa+\Delta\rho g^2/\kappa^2 = D_2 = 0\,. \quad (4)$$

The two solutions of this equation for long waves are

$$c_1 = \sqrt{g(h_1+h_2)} \quad \text{and} \quad c_2 = \sqrt{\Delta\rho g\, h_1h_2/(h_1+h_2)}\,. \quad (5)$$

The velocity c_1 is valid for waves at the surface, which are associated with displacements of the boundary layer of smaller amplitudes than those at the surface. c_2 is the velocity of free internal waves.

In the case of *forced* waves the case of *resonance* corresponds to $D_2 = 0$. Theoretically the amplitude of forced waves will be infinitely large. Note that the internal waves will be infinitely large if the condition $c = c_2$ is exactly fulfilled. But this never occurs, since the magnitude of c for tidal waves in the oceans is about 200 m/sec and that of c_2 only 2 m/sec. The same is true for the more general equation (3) which also contains the influence of steady currents. For values of c, U_1 and U_2 that occur in nature, D_1 is a very large number, so that the generated internal waves will remain small—much smaller than those at the surface. Consequently they are not internal waves in a strict sense.

The same conclusions follow from the computation of the ratio of the amplitudes of the two generated tide waves. One finds with good approximation:

$$\frac{\zeta_1}{\zeta_2} = 1 - \frac{(c - U_2)^2\, h_1/h_2}{gh_1\Delta\rho - c(c - U_1)\,\rho_1/\rho_2}\,. \quad (6)$$

Since internal waves have larger amplitudes on the boundary layer:

$$\Delta\rho g h_1 - c(c - U_1)\rho_1/\rho_2 \geqq (c - U_2)^2 h_1/h_2\,.$$

Since $c >> U_1$ and U_2,

$$c^2 \leqq \Delta\rho g\, h_1h_2/(h_1+h_2)\,;$$

in other words, c must be smaller than the velocity of *free* internal waves. However, this is never the case. We see that this factor does not contribute to the generation of large internal waves. This factor has been considered in greater detail by Haurwitz (1948), who arrives at essentially the same conclusion.

The condition $D_1 = 0$ has another significance which needs a few words of explanation. The solution (3) for c leads to a few difficulties. Since we want internal waves for which amplitudes of contemporary waves at the surface are extremely small, we may take, with good approximation, this amplitude equal to zero. Then we replace the surface by a rigid horizontal plane, in which the vertical motions are zero. The solution for c is then:

$$c = \frac{\rho_1 U_1 \omega_1 + \rho_{22} U \omega_2}{\rho_1 \omega_1 + \rho_2 \omega_2} \pm \sqrt{\frac{g}{\kappa} \frac{\rho_2 - \rho_1}{\rho_2 \omega_2 + \rho_1 \omega_1} - \rho_1 \rho_2 \omega_1 \omega_2 \left(\frac{\rho_2 - \rho_1}{\omega_2 \rho_2 + \omega_1 \rho_1} \right)^2} . \quad (7)$$

The first term on the right side is the convection velocity which corresponds approximately to a mean velocity of two currents. The first term below the root is the velocity of free internal waves; the second term with the negative sign, which always decreases the stability of the internal waves, gives the velocity of inertial waves. Dynamic instability will occur if this term is larger than the first, and therefore the condition for dynamically unstable internal waves will be:

$$(U_2 - U_1)^2 > \frac{g}{\kappa} (\rho_2 - \rho_1)[1/\rho_1 \omega_1 + 1/\rho_2 \omega_2] . \quad (8)$$

This criterion of stability is discussed in all its details by Bjerknes, et al. (1933) from the point of view of the generation of cyclones in the atmosphere. Here we are interested with the question as to when dynamic instability occurs in the ocean. The condition for this is:

$$(U_2 - U_1) > \sqrt{\frac{\rho_2 - \rho_1}{\rho_1 \rho_2} (\rho_2 h_1 + \rho_1 h_2) g} . \quad (9)$$

If h_2 is large, which is the case in the open sea, the inequality is reduced to $(U_2 - U_1) > \sqrt{\Delta \rho \, g h_2}$. The quantity on the right-hand side is always large, since h_2 is large, even with small $\Delta\rho$. Such steady currents will not occur in nature, and the inequality (9) is never fulfilled. Hence internal tide waves are always stable in the open ocean. But on shelf water or in shallow straits internal waves may easily become unstable. If $h_1 = h_2$, we have

$$U_2 - U_1 > \sqrt{g h_1 \frac{\rho_2^2 - \rho_1^2}{\rho_1 \rho_2}} , \quad (10)$$

with $h_1 = 100 - 150$ m, $U_2 - U_1 > \frac{1}{2}$ to 1 m/sec. This velocity difference is easily reached by steady currents. In fact, observations at anchor stations in straits have shown that normal stable internal waves can become unstable (Defant, 1948). The observations at anchor stations by the DANA Expedition in the Strait of Gibraltar during the spring of the year show distinctly that large internal waves will be unstable, thus leading to internal surf. Also, internal waves on the shelf off the West African Coast tend towards instability and formation of internal surf. This surf may destroy the thermocline, and only in this case will the phenomenon of upwelling of cold water develop off the coast. The instability of internal waves is still more pronounced in the Strait of Messina, where it produces the famous eddies of Scylla and Charybdis (Mazarelli, 1938; Defant, 1940). When the boundary layer between the converging tidal currents in the two water masses is brought to the surface on one side of the Strait by Coriolis' force, the instability of the internal waves will generate a large eddy. Undoubtedly these eddies are nothing but the effect of dynamic instability of internal waves in this shallow Strait.

The two points of view just discussed lead to negative results. I will now discuss a third point of view, which may account in part at least for the generation of internal tide waves. Until now we have neglected the Coriolis' force. Perhaps this force can be neglected in the first approximation in small regions or in narrow straits, but in the open ocean this is surely not permissible. Since we have already shown that the steady current in the two superposed water masses does not lead to large internal waves, we can disregard those currents. By working with long waves we can neglect the vertical accelerations; the equations of motion of the system are:

$$\begin{aligned} \frac{\partial u_1}{\partial t} &= \lambda v_1 - g\frac{\partial \zeta_1}{\partial x} + X, & \frac{\partial u_2}{\partial t} &= \lambda v_2 - g\frac{\rho_1}{\rho_2}\frac{\partial \zeta_1}{\partial x} - g\Delta\rho\frac{\partial \zeta_2}{\partial x} + X, \\ \frac{\partial v_1}{\partial t} &= -\lambda u_1 - g\frac{\partial \zeta_1}{\partial y}, & \frac{\partial v_2}{\partial t} &= -\lambda u_2 - g\frac{\rho_1}{\rho_2}\frac{\partial \zeta_1}{\partial y} - g\Delta\rho\frac{\partial \zeta_2}{\partial y}, \end{aligned} \tag{11}$$

where X is given by (2) and $\lambda = 2\Omega \sin \varphi$ is the Coriolis' parameter; the influence of friction is neglected. To these dynamic equations must be added the equation of continuity for both layers:

$$\begin{aligned} &\frac{\partial \zeta_1}{\partial t} + h_2\left[\frac{\partial u_2}{\partial x} + \frac{\partial v_2}{\partial y}\right] + h_1\left[\frac{\partial u_1}{\partial x} + \frac{\partial v_1}{\partial y}\right] = 0 \\ &\frac{\partial \zeta_2}{\partial t} + h_2\left[\frac{\partial u_2}{\partial x} + \frac{\partial v_2}{\partial y}\right] = 0\,. \end{aligned} \tag{12}$$

If we take

$$\frac{u_1}{v_1} = \frac{U_1}{V_1} e^{i(\sigma t - \kappa x)}, \qquad \frac{u_2}{v_2} = \frac{U_2}{V_2} e^{i(\sigma t - \kappa x)} \quad \text{and} \quad \frac{\zeta_1}{\zeta_2} = \frac{Z_1}{Z_2} e^{i(\sigma t - \kappa x)},$$

then the previous system of equations gives six equations for computing the six unknowns U, V, Z. With

$$\frac{\sigma^2 - \lambda^2}{\kappa^2} = \varepsilon^2, \tag{13}$$

we have as denominator of all these quantities the expression:

$$\varepsilon^4 - (h_1 + h_2) g \varepsilon^2 + \Delta\rho g^2 h_1 h_2 = D_3 . \tag{14}$$

It has the same form as the relation (4), transformed for tidal waves. But instead of being the velocity of forced waves, c enters the influence of the earth's rotation through the quantity ε. Whereas c has the magnitude of 200 m/sec and the quantity D_2 is a large number, as shown before, under certain conditions ε can be small or nearly equal to the velocity of free internal waves. With these values, however, D_3 will be zero. If T_i is the period of inertial waves (equal to 12 pendulum hours), then

$$\varepsilon^2 = c^2[1 - (T/T_i)^2] . \tag{15}$$

For the diurnal tide wave, $T = 24$ hours and ε will be zero at 30° latitude, but for the semidiurnal lunar wave, $T = 12.43$ hours and ε will be zero at 74° latitude.

For small ε equation (14) has, in the first approximation, the form:

$$D_4 = \Delta\rho g^2 h_1 h_2 - g(h_1 + h_2)\varepsilon^2 .$$

D_4 will be zero for

$$\varepsilon^2 = \Delta\rho g \, h_1 h_2/(h_1 + h_2) . \tag{16}$$

When $\varepsilon = c_2 =$ the velocity of free internal waves, then *resonance* exists for forced internal waves. In other words, the amplitudes of internal tide waves will be very large at these latitudes. This is not the case for the normal tides at the surface, for which

$$D_5 = \varepsilon^2[\varepsilon^2 - g(h_1 + h_2)] . \tag{17}$$

D_5 remains a large number when $\varepsilon = c_2$.

Therefore, the rotation of the earth provides a factor which is able to increase the amplitudes of internal waves, and internal waves will thus be a larger wave motion than the tide at the surface.

If we add steady currents to the two superposed layers, the denominator assumes, for forced internal waves, the form

$$(c - U_2)^2 \left[1 - \frac{\lambda^2}{(\sigma - \kappa U_2)^2}\right] h_1 + \frac{\rho_1}{\rho_2}(c - U_1)^2 \left[1 - \frac{\lambda^2}{(\sigma - \kappa U_1)^2}\right] h_2$$

$$- \Delta\rho g h_1 h_2 = D_6\,. \quad (18)$$

The term with Coriolis' parameter will be changed only insofar as we have $(\sigma - \kappa U)^2$ instead of σ^2. The influence of this change goes in the desired direction of increasing the resonance, but the effect is very small.

In the foregoing results there is one difficulty, which I wish to discuss. The width of the resonance area is very small, at most 2 to 3 degrees of latitude. Outside this small strip, D_3 is always large and the amplitudes of internal waves will not be influenced greatly by the rotation of the earth. This surprising result, however, is the consequence of the way the problem has been formulated. The difficulties are the same as those in the theory of surface tides, and they can be removed if the boundary conditions are taken into account.

Finally, the equations of the problem show directly that the rotation of the earth must have a great influence upon internal wave motion. We will suppose in this case that the density increases in an arbitrary manner with depth. Eliminating pressure from the equation of motion,

$$\begin{aligned} \frac{\partial\rho}{\partial x} &= \frac{\lambda}{g}\frac{\partial\rho v}{\partial z} - \frac{1}{g}\frac{\partial\rho\dot{u}}{\partial z} \\ \frac{\partial\rho}{\partial y} &= -\frac{\lambda}{g}\frac{\partial\rho u}{\partial z} - \frac{g}{g}\frac{\partial\rho\dot{v}}{\partial z}\,, \end{aligned} \quad (19)$$

where the z-axis is positive downwards. If $u = u_0 \sin\sigma t$ and $v = v_0 \cos\sigma t$ designate tidal currents, then (19) gives

$$\frac{\partial\rho}{\partial x} = \frac{\sigma}{g}\left[s\frac{\partial\rho v_0}{\partial z} - \frac{\partial\varphi u_0}{\partial z}\right]\cos\sigma t\,,$$

$$\frac{\partial\rho}{\partial y} = \frac{\sigma}{g}\left[\frac{\partial\rho v_0}{\partial z} - s\frac{\partial\rho u_0}{\partial z}\right]\sin\sigma t\,, \quad (20)$$

where $s = \lambda/\sigma$. To these equations we must add the equation of continuity, and, as shown by Fjeldstad in his theory of internal waves, we obtain equations for u and v in which the denominator is again the quantity ε. With the same values of T, resonance will occur in the same latitudes. But the equations (20) already show clearly that internal waves are also associated with a variation of the density gradient with depth. If internal waves exist only in the y-direction, then $\partial\rho/\partial x = 0$, and we have $u_0 = s\,v_0$; in other words, the tidal current u in the x-direction will then be

$$\frac{\partial\rho}{\partial y} = \frac{\sigma}{g}\,\varepsilon^2 v_0 \frac{\partial\rho}{\partial z} \sin\sigma t\,, \tag{21}$$

provided the tidal current v is independent of z, as in the case of simple tidal waves. This means that every change in density with depth is followed by a periodical sinking and rising of isopycnals across the tidal current. As a numerical example, take
$v_0 = 1$ m/sec, $\sigma_s = 1.45 \times 10^{-4}\,\mathrm{sec}^{-1}$, and $\lambda = 0.7 \times 10^{-4}\,\mathrm{sec}^{-1}$ and $\Delta\rho/\Delta z = 4 \times 10^{-3}\,\mathrm{g\,cm}^{-3}$ per 30 m $= 1.33 \times 10^{-6}\,\mathrm{g\,cm}^{-4}$. This gives $\Delta\rho/\Delta y = 1.52 \times 10^{-11}\,\mathrm{g\,cm}^{-4}$; that is, the isopycnals show an elevation of 5.7 m over a distance of 500 km. The range of internal waves is 11.4 m. Therefore, strong tidal current must always be connected with large internal waves, and it is not surprising that the oceanographic observations at anchor stations in the open ocean always show large internal waves. If we wish to eliminate these waves from the observations of oceanographic surveys, we must know the law to which they are subjected. But we are still far from this aim.

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Contribution No. 472

riation in the Earth's Angular Velocity Resulting from Fluctuations in Atmospheric and Oceanic Circulation[1]

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Abstract

Fluctuations in the circulation of the atmosphere are associated with very small anomalies in the angular velocity of the earth. The seasonal component of these anomalies has been computed from weather maps, and is found to agree, with respect to magnitude and phase, with anomalies first reported by STOKYO in 1936 on the basis of astronomic observations. The effects of fluctuations in the oceanic circulation, and of shifting of air and water masses, have been estimated to account for not more than 15 per cent of the observed effect.

The detection of shorter period fluctuations is presently limited by the accuracy of astronomic time determination. The developments of an atomic clock and of the photographic zenith tube open the possibility of determining anomalies persisting for only two weeks, and of providing a new tool for obtaining an index of *integrated* atmospheric circulation.

ıction

problem is well stated by STARR (1948):

> 'Although it is true that the combined tem composed of the earth and the nosphere cannot alter its total absolute gular momentum except for extremely w secular changes resulting from tidal ion as was pointed out by Darwin and ıers, still there is no reason to expect ıt the partition of angular momentum the composite system should remain nstant when seasonal and other short ıe-intervals are considered. Because of great contrast in the moments of iner- of the two components, short-period anomalies of this kind represent major anomalies in the behavior of the wind system, but, on the other hand, imply practically undetectible inequalities in the rate of the earth's rotation."

WIDGER (1949) affirms that "there is little hope" of detecting these minute inequalities. Actually such inequalities have been reported, although not interpreted, by NICOLAS STOYKO, a French astronomer, in 1936, 1937, and 1949. Similar observations have been made by SCHEIBE and ADELSBERGER in Germany and by FINCH in England.

In a recent paper VAN DEN DUNGEN et al. (1949) have ascribed the fluctuations observed by STOYKO to seasonal shifts in air mass. Their computations (for the northern hemisphere only) account for 20 per cent of the observed effect, and the discrepancy is laid to uncer-

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tainties in the various assumptions. We have recomputed this effect, taking into account the corresponding shift of air mass in the southern hemisphere (which largely compensates for the shift in the northern hemisphere), the local pressure variations rather than those reduced to sea level, and the tendency of the ocean water to redistribute itself under the influence of changing atmospheric pressure. Each of these factors substantially reduces the effect, and the computed anomalies in the earth's rotation resulting from the shift in air masses amounts to less than 2 per cent of the observed effect. The fluctuations in the angular momentum of the atmospheric circulation is, however, of the right magnitude to account for the observed effect.

Conservation of angular momentum

Neglecting secular changes resulting from tidal friction,

$$I_e\Omega_e + I_a(\Omega_e + \omega_a) + I_o(\Omega_e + \omega_o) = \text{constant}, \quad (1)$$

where I_e, I_a and I_o are the moments of inertia of the solid earth, atmosphere and ocean, respectively, Ω_e the earth's absolute angular velocity, ω_a and ω_o the components along the earth's axis of the *relative* angular velocities of atmosphere and ocean. Differentiation gives

$$-\frac{\Delta\,\Omega_e}{\Omega_e} = \frac{\Delta\,(I_a\omega_a)}{I\Omega_e} + \frac{\Delta\,(I_o\omega_o)}{I\Omega_e} + \frac{\Delta\,I}{I}, \quad (2)$$

where $I = I_e + I_a + I_o$

Angular momentum of the atmospheric circulation

The relative angular momentum of the atmosphere between the levels h_1 and h_2, the latitudes φ_1 and φ_2, and the longitudes Θ_1 and Θ_2, is given by

$$I_a\,\omega_a = R^3 \int_{h_1}^{h_2}\int_{\varphi_1}^{\varphi_2}\int_{\Theta_1}^{\Theta_2} \varrho u \cos^2\varphi \, dh\, d\varphi\, d\Theta. \quad (3)$$

where R is the radius of the earth, ϱ the density and u the zonal wind. The largest portion of the angular momentum is contained in the "jet stream" and surrounding westerlies, which extend approximately from 25° to 60° latitudes. The values in Table 1 have been co
from weather maps by numerical int
along vertical sections from the su
17 km. For the northern hemisphere[3]
along 100° E and 80° W longitudes we
It is assumed that those sections are rep
tive of conditions throughout 90° of lo
to either side. Only one section is avail
the southern hemisphere (LOEWE and
1950), but it must be realized that this
is far from typical for other longitud
easterlies have been taken into acc
the northern hemisphere, but not in th
ern hemisphere where the belt of eas
narrow and their effect comparativel

According to Table 1 the seasonal v
in the southern hemisphere amounts
than one third the seasonal variation
northern hemisphere. The reason for
twofold: (*a*) the jet stream in the s
hemisphere during the southern winte
rower than the northern jet stream
northern winter; (*b*) the westerlies
southern hemisphere during the southe
mer are very much stronger than the w
in the northern hemisphere during the n
summer. The seasonal variation in the s
hemisphere may be even smaller than in
in Table 1, since our calculations are b
geostrophic winds, and these are almos
the observed zonal winds at Townsvill
bane and Sydney during the southern
No wind observations are available
summer season.

Table 1. Relative angular momentum of
mosphere in units of 10^{32} g cm² sec^{-1}. The
ern hemisphere is divided in two parts, ce
at stated longitudes.

	Northern Hemisphere			Sc He
	100° E	80° W	Total	
$I_a\omega_a$, January	6.8	5.9	12.7	
$I_a\omega_a$, July	0.2	−0.1	0.1	
$\Delta\,(I_a\omega_a)$	6.6	6.0	12.6	—

Setting $\Delta\,(I_a\omega_a) = 9 \times 10^{32}$ g cm²
$I \approx I_e = 0.8 \times 10^{45}$ g cm², $\Omega_e = 0.73$
sec^{-1}, gives a relative seasonal range of

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[3] We are indebted to Dr YALE MINTZ of the M
ogy Department at the University of California
Angeles for making available the mean month
section on which our calculations for the norther
sphere are based.

$$\frac{\Delta(I_a \omega_a)}{I \Omega_e} = 1.6 \times 10^{-8},$$

out one part in sixty million.

lar momentum of oceanic circulation

estimate fluctuations in the angular mo-
um of the ocean circulation we have
uted numerically the angular momentum
wo of the largest ocean current systems
RDRUP et al., 1946, pp. 614, 710):

tarctic Circumpolar Current:
1.0×10^{32} g cm^2 sec^{-1}

uatorial Easterly Currents, all oceans:
0.5×10^{32} g cm^2 sec^{-1}.

e angular momentum of the entire zonal
lation of the oceans is perhaps 3 to 4 × 10^{32}
^{2} sec^{-1}, and the range in fluctuations
bly not more than 20 per cent of this
, or

$$\frac{\Delta(I_o \omega_o)}{I \Omega_e} \approx 0.15 \times 10^{-8}.$$

may seem surprising that the ocean cir-
on should contribute only one eighth of
of the atmosphere, especially since the
of the atmosphere corresponds to only
eters of water compared to a mean ocean
of 4,000 meters. However the mean
velocity of the ocean water is probably
han 2 cm/sec, whereas the mean zonal
speed in the westerlies (weighted for
ty stratification) is 20 m/sec. Thus the
in masses of 400 : 1 is more than offset by
locity ratio of 1 : 1,000. An additional
is the larger *percentage fluctuations* of the
spheric circulation about its mean value.

ent of inertia

e third term on the right side of equa-
(2) includes changes in the moment of
a of the atmosphere, the ocean and the
Changes in the ocean are due partly
e effect of wind stress (to be considered
, partly to the effect of atmospheric
ire on the sea surface in redistributing the
s of the ocean. We shall consider two
ne cases: the case of immovable water,
as if the entire ocean were frozen, and the case for which complete equilibrium has been achieved. For seasonal variations equilibrium is probably nearly attained. Very short period fluctuations fall into the first category.

For the case of immovable ocean water we have estimated ΔI_a according to the equation

$$\Delta I_a = \frac{R^4}{g} \int_{-\pi}^{\pi} \int_{0}^{2\pi} \Delta p \cos^3 \varphi \, d\varphi \, d\Theta, \qquad (4)$$

where Δ again represents January values minus July values. The mass of air above a unit area of the earth's surface was set equal to p/g, and p determined from normal monthly weather maps (U. S. Weather Bureau, 1946, and BRUNT, 1939, pp. 8—9). In equation (4) p is the *local* pressure, and not the corresponding value reduced to sea level, as it is given on climatic charts.[4] Accordingly it was necessary to remove the sea level correction from the p values on the monthly weather charts (JEFFREYS, 1929, pp. 239—244). Values of Δp for pressures reduced to sea level, and for local pressure variations, are shown in Table 2. The quantities $[\Delta p]$ in Table 2 represent averages around the stated latitude circles. In general the local pressure variations are smaller than corresponding sea level pressure variations, and in high latitude the two variations are opposite in sign. Consequently the seasonal changes in the moments of inertia are substantially reduced when allowance is made for the elevation of the meteorological stations. In the northern hemisphere the reduction is by a factor of 2.7, in the southern hemisphere by only 6 per cent. For both hemispheres $\Delta I_a = -0.83 \times 10^{36}$ g cm^2 compared to a value of *plus* 1.8×10^{36} g cm^2 obtained by VAN DEN DUNGEN et al. (1949).

The value of ΔI_a is even further reduced if the ocean water is permitted to move to attain equilibrium. We adapt a method given by JEFFREYS (1929). Let Δm designate the change (January minus July) per unit surface area of the *combined* mass of air and water. Conservation of mass requires that

$$\iint_E \Delta m \, ds = \iint_o \Delta m_o \, ds + \iint_L \Delta m_L \, ds = 0,$$

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[4] The error resulting from the use of sea level pressure has already been pointed out by Angot. See Annuaire de la Société Météorologique de France, T. 35, 1887.

Table 2. Computation of ΔI_a (pressure in mb).

Latitude	Sea level pressure		Local pressure		Local pressure	
	$[\Delta p]$	$\int_0^{2\pi} \Delta p \cos^3 \varphi \, d\Theta$	$[\Delta p]$	$\int_0^{2\pi} \Delta p \cos^3 \varphi \, d\Theta$	$\int_L \Delta p \cos^3 \varphi \, d\Theta$	$\int_L \Delta p$ cc
Northern Hemisphere						
80—85	1.1	0.0	— 0.7	0.0	0.0	—
75—80	1.3	0.1	— 1.1	— 0.1	— 0.2	—
70—75	0.7	0.1	— 1.7	— 0.3	— 0.3	—
65—70	2.6	0.9	0.2	0.1	0.6	
60—65	3.4	2.1	— 2.2	— 1.4	— 0.3	—
55—60	3.5	3.5	0.0	0.0	2.2	
50—55	4.1	5.9	— 2.2	— 3.2	0.9	
45—50	4.4	8.6	— 1.9	— 3.7	2.7	
40—45	4.9	12.3	— 0.5	— 1.3	4.4	
35—40	5.5	17.2	— 0.1	— 0.3	3.1	
30—35	6.3	23.8	0.1	0.2	— 0.4	—
25—30	6.9	30.0	0.5	2.2	— 1.7	—
20—25	6.4	31.7	5.7	28.3	18.7	2
15—20	4.7	25.5	4.0	21.9	9.0	
10—15	2.3	13.4	2.2	12.6	3.7	
5—10	1.4	8.4	1.2	7.3	— 0.4	—
0—5	1.4	8.5	1.4	8.7	1.1	
Σ		192.0		71.0	43.1	5
ΔI_a in 10^{36} g cm²		2.81		1.04	0.63	
Southern Hemisphere						
0—10	— 2.7	— 17.1	— 2.7	— 16.8	— 5.8	—
10—20	— 4.4	— 25.0	— 4.1	— 23.1	— 7.4	—
20—30	— 5.4	— 24.6	— 4.8	— 22.1	— 6.0	—
30—40	— 1.6	— 5.5	— 1.6	— 5.4	— 0.4	—
40—50	2.0	4.5	2.0	4.5	0.1	
50—60	1.3	1.5	1.3	1.5	0.0	
60—70	— 4.0	— 1.9	— 4.0	— 1.9	0.0	
70—80	— 2.1	— 0.2	— 2.1	— 0.2	— 0.1	—
Σ		— 68.3		— 63.5	— 19.6	— 2
ΔI_a in 10^{36} g cm²		— 2.00		— 1.87	— 0.57	
Both hemispheres ΔI_a		0.81		— 0.83	0.06 — 0.08 (equ. 6) — 0.02	

where the subscripts refer to integration over the entire surface of the earth, over the ocean areas, and over the land areas, respectively. The ocean water will move in such a manner that Δm_o has the same value over the entire ocean area. It follows that

$$\iint_o \Delta m_o \, ds = \Delta m_o \iint_o ds = \Delta m_o S_o$$

$$= -\iint_L \Delta m_L \, ds = -\overline{\Delta m_L} \iint_L ds = -\overline{\Delta m_L} \, S_L$$

or

$$\Delta m_o = -\frac{S_L}{S_o} \overline{\Delta m_L},$$

where $\overline{\Delta m_L}$ represents a mean value over that portion of the earth's surface is covered by land.

Changes in the moment of inertia ar posed of those occurring over the oce those occurring over land:

$$\Delta I_a = R^2 \Delta m_o \iint_o \cos^2\varphi\, ds +$$

$$+ R^2 \iint_L \Delta m_L \cos^2\varphi\, ds =$$

$$= - R^2 \frac{S_L}{S_o} \frac{\overline{\Delta p_L}}{g} \iint_o \cos^2\varphi\, ds +$$

$$+ \frac{R^4}{g} \int_{-\pi}^{\pi}\int_L \Delta p_L \cos^3\varphi\, d\varphi\, d\Theta, \qquad (6)$$

re $\Delta p = g\Delta m$, and

$${}_L = g\,\overline{\Delta m_L} = \frac{R^2}{S_L} \int_{-\pi}^{\pi}\int_L \Delta p_L \cos\varphi\, d\varphi\, d\Theta \qquad (7)$$

e mean (local) pressure variation over all . The computation is summarized in Table or the earth, $S_L/S_o = 0.419$, $S_E = S_L +$ ${}_o = 5.10 \times 10^{18}$ cm², $\iint_o \cos^2\varphi\, ds =$ .49 S_E, $\overline{\Delta P_L} = 0.183$ mb $= 183$ dynes ², and the first term in (6) reduces to .32 × 10^{32} $\overline{\Delta P_L} = - 0.08 \times 10^{36}$ g cm², pared to $+ 0.06 \times 10^{36}$ g cm² for the nd term. In view of the uncertainty of calculations, this high degree of cancella- is largely fortuitous, and the final value I_a may be as large as 0.25×10^{36} g cm² of either sign. We shall adopt this larger e. For comparison, the moment of inertia one meter snow cover, or 20 cm water er, over the entire United States is also × 10^{36} g cm². It would be desirable to mpute Table 2 using the original data the uncorrected local pressure.

larger effect is related to the shifting of n currents, and the distribution of mass ciated with the currents, by the variable ds. This effect could best be computed n seasonal changes in the topography of the surface as obtained either from standard nographic observations of density versus th, or from tide gauges. Unfortunately e are very few ocean areas from which eated oceanographic observations have shed t on seasonal variations. Many tide gauge ords show seasonal variations in sea level) of the order of 20 cm, but almost all e variations are associated with coastal ents and other local phenomena.

In order to obtain a rough estimate of the sea level effect on a world-wide basis we have noted a relationship (MUNK, 1950) between the mean annual sea level in the Atlantic from 50° N to 60° S, and the corresponding distribution of atmospheric pressure over the same area. Both the sea level and the pressure reach maxima in 30° N and 30° S and drop sharply towards higher latitudes. The "dynamic sea level" is therefore opposite in phase from the "hydrostatic sea level" previously considered. To obtain a numerical relationship we must first subtract the hydrostatic effect and write

$$\frac{\varrho_w\, g\, z_w + p_{\text{atm}}}{p_{\text{atm}}} = \lambda,$$

where ϱ_w is the density of water, z_w the deviation of sea level from its mean, and λ a proportionality factor which varies from 2.5 near the equator to about 7.5 at 60°, and can be represented by $\lambda = 2.5 + 5\varphi^2$, where φ is the latitude in radians.

We now assume that this relationship $\lambda(\varphi)$ can be applied to seasonal variations over all ocean areas, and thus compute the dynamic sea level effect from the known seasonal pressure variations according to

$$\Delta I_o = \frac{R^4}{g} \int_{-\pi}^{\pi}\int_o \lambda\,(\Delta p_o - \overline{\Delta p_o})\, \cos^3\varphi\, d\varphi\, d\Theta, \qquad (8)$$

where $\overline{\Delta p_o} = -(S_L/S_o)\,\overline{\Delta p_L} = -0.77$ mb is the mean pressure variation over all oceans. At any latitude

$$\int_o \lambda\, \Delta p_o \cos^3\varphi\, d\Theta = \lambda\Big\{\int_o^{2\pi} \Delta p \cos^3\varphi\, d\Theta -$$

$$- \int_L \Delta p \cos^3\varphi\, d\Theta\Big\},$$

and the first term in (8) can be obtained by subtracting Column 6 from Column 5 in Table 2, and multiplying by appropriate values of λ. The second term,

$$-\frac{R^4}{g}\,\overline{\Delta p_o} \iint_o \lambda(\varphi)\, \cos^3\varphi\, d\varphi\, d\Theta$$

has been evaluated numerically and equals 1.3×10^{36} g cm² over the northern hemisphere and 1.8×10^{36} g cm² over the southern hemisphere. The results are

ΔI_o, northern hemisphere 1.4×10^{36} g cm²
ΔI_o, southern hemisphere -2.2×10^{36} g cm²
ΔI_o, both hemispheres -0.8×10^{36} g cm².

The extrema in pressure changes and in the computed dynamic sea level changes are summarized in Table 3.

Table 3. Extrema in pressure changes ($\Delta p_o - \overline{\Delta p}$) and sea level changes Δz

Latitude	λ	$\Delta p - \overline{\Delta p_o}$ mb	Δz cm
67° N	9	+ 3	+ 27
57° N	7	— 5	— 35
20° N	3	+ 4	+ 12
20° S	3	— 3	— 9
50° S	6	+ 3	+ 18
70° S	10	— 3	— 30

The computed changes in sea level are of the same magnitude as those obtained from tide gauge records.

There remain the changes ΔI_e in the inertia of the solid earth and biosphere. To the first of these have been ascribed rather abrupt changes in $\Delta \Omega_e/\Omega_e$ as large as 4.0×10^{-8}, which appear to occur every two or three decades. Whatever the cause of these intermittent changes, it is unlikely that *seasonal* changes in the moment of inertia of the solid earth are of sufficient magnitude to compare with the effects discussed above[5]. The effects of vegetation, related to the rise of sap from the ground into the woody part of trees, of the production of leaves, and of other factors, have been estimated by JEFFREYS (1929) to have a seasonal range of 2 g cm^{-2} in the temperate zones, corresponding to a change in the moment of inertia by 0.15×10^{36} g cm² for the northern hemisphere. Compared to these values, any direct effect of human activity is negligible. If all American automobiles were driven from Alaska to Mexico, the change in the moment of inertia would amount to only 10^{31} g cm².

The combined changes of inertia of atmosphere, ocean and earth probably do not exceed 1.00×10^{36} g cm². This leads to a value of $\Delta I/I = 0.12 \times 10^{-8}$.

Summary of seasonal fluctuations

The interrelationships between the va atmospheric and oceanic terms appearin the right side of equation (2) is sketch fig. 1. The magnitudes are as follows:

$\Delta(I_a \omega_a)/I\Omega_e$ .... $+ 1.6 \times 10$
$\Delta(I_o \omega_o)/I\Omega_e$ .... 0.15×10
(plus or mi
$\Delta I/I$ .... 0.12×10
(plus or mi

The term on the left side of equation $-\Delta\Omega_e/\Omega_e$, has been determined by ST (1936, 1937, 1949) and FINCH (1950) astronomic observations:

STOYKO

1934—1935	2.93×10^{-8}
1935—1936	0.76×10^{-8}
1936—1937	1.59×10^{-8}
1946—1947	2.40×10^{-8}

FINCH

1943—1947	2.0×10^{-8}
1948—1949	2.3×10^{-8}

Here $\Delta\Omega_e$ represents January rotation m the preceeding July rotation.

The observations for 1934—1935 ca compared to those by SCHEIBE and A BERGER (1936). These give 1.4×10^{-8}

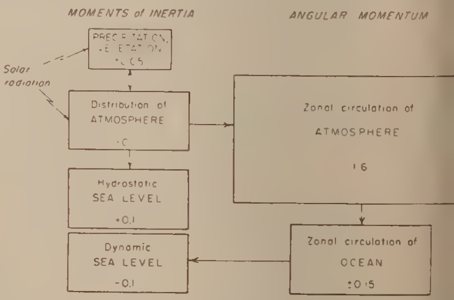

Fig. 1. Schematic presentation of the relationship tween factors influencing the earth's angular velocity. numbers give an indication of the seasonal effect of factor, expressed in parts per hundred million of the r rate of rotation, or roughly in milliseconds per (+) represents excess of earth's rotation in July over in January. (±) represents magnitude without indica of the direction of the effect. Sea level changes are c posed of those induced by the hydrostatic pre changes, and those related to the oceanic circula which in turn is caused by the winds.

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[5] Dr Mintz has pointed out the interesting possibility that seasonal variations in the solar tides may have an important effect.

0^{-8}, depending on whether the differ-
anuary minus July or January minus
are formed. For the preceeding year
sonal variation appears to be small
scured by the scatter of data.
meteorologic and astronomic observa-
ree with regard to both magnitude and
he astronomic observations reveal a
ce in rotation between March and
which is, on the average, 80 per cent
han the difference between January and
he meteorologic implication of this ob-
n is not at all in disagreement with
c experience.

cy of determining earth's angular
y

detection of short period anomalies in
ospheric circulation is likely to be of
practical interest in meteorology than
sonal fluctuations. Whether the earth's
can be determined with sufficient
y to make this possible depends largely
factors: the accuracy of time deter-
n from the zenith passage of stars, and
ecision of the clocks with which the
mic time is to be compared.
sing a "bank" of *quartz crystal clocks*, and
g" the clocks against one another, it has
ossible to achieve a relative accuracy of
rt in a hundred million. The term rela-
used, because it is found that the fre-
characteristics of the crystals undergo
small changes from time to time, and
cks must be compared to some in-
ent time standard, i.e., the mean annual
the earth's rotation. In 1898, and again
o, the mean annual rate of rotation
d rather abruptly, and during those
determination of the seasonal compo-
f the earth's angular velocity would have
erroneous results.
development of *atomic* clocks promises
ide an absolute time standard independ-
the earth's rotation. In the case of the
ia clock now being developed by LYONS
a constancy of one part in 20 million has
chieved, and an accuracy of one part in
llion is hoped for. However, in another
pment carried on by the Bureau of
rds with the assistance of Professor P.
of Columbia University, quantum

transitions in beams of atoms such as *cesium* will be used to establish frequency and time standards. The potential accuracy is increased (Bureau of Standards, 1949) "by a factor of 10 to 100 or more", and "an ultimate accuracy of 1 part in 10 billion may be reached."

A quite different limitation is imposed by the accuracy to which the "earth clock" and the atomic clock can be *read* in order to measure the cumulative difference between the rates of the two clocks. In practice only the accuracy in reading the earth clock need be considered. The present accuracy of astronomic time determination is about 0.02 seconds. According to the Astronomer Royal (SPENCER JONES, 1945) the proposed installation at the Royal Observatory of 18 quartz crystal standard clocks in conjunction with the photographic zenith tube will reduce the probable error in time determination to 0.002 or 0.003 seconds. Dr. SOLLENBERGER at the U. S. Naval Observatory estimates (personal communication) that the error can ultimately be reduced to 0.001 or 0.002 seconds.

We may interpret these values in terms of the probable accuracy to which the earth's angular velocity can be determined. Suppose we wish to measure the mean angular velocity of the earth during a period of N days, starting with $t = -{}^1/_2\,N$ and ending with $t = +{}^1/_2\,N$. Once each day we determine the difference x between the astronomic time y and the clock time z. The slope m of the line $x = f(t)$ equals

$$m = \frac{\Delta\,\Omega_e}{\Omega_e} = \frac{\sum\limits_{t=-N/2}^{N/2} x_i\,t_i}{\sum\limits_{t=-N/2}^{N/2} t_i^2}$$

by the methods of least squares, with the understanding that the mean value of x has been subtracted from the individual values.

The probable error m' of m equals the geometric sum of the probable errors of each term in the series:

$$m'^2 = \frac{\sum\limits_{t=-N/2}^{N/2} (x_i'\,t_i)^2}{\left(\sum\limits_{t=-N/2}^{N/2} t_i^2\right)^2}. \tag{9}$$

The probable error x_i' of $x_i = y_i - z_i$ equals the geometric sum of the probable errors of y_i and z_i:

$$x_i'^2 = y_i'^2 + z_i'^2.$$

Here y_i' is the error in astronomic time determination, which remains constant throughout the time interval N. The probable clock error may be set as $z_i' = \omega' t_i$, where ω' is the constant probable error in the *rate* of the clock relative to its mean rate. Substituting

$$x_i'^2 = y'^2 + \omega'^2 t_i^2$$

into Equation (9) leads to

$$2\, m'^2 = \frac{y'^2}{F} + \frac{f\omega'^2}{F^2}, \qquad (10)$$

where

$$F(N) = 1^2 + 2^2 + \ldots (N/2)^2 = \frac{N^3}{24} + \frac{N^2}{8} + \frac{N}{12},$$

$$f(N) = 1^4 + 2^4 + \ldots (N/2)^4 = \frac{N^5}{160} + \frac{N^4}{32} + \frac{N^3}{24} - \frac{N}{60}.$$

Both N and y' are given in days.

The uncertainties in the astronomic time determination and in the rate of the clock contribute equally to the uncertainty in the determination of the earth's rotation if

$$\frac{y'^2}{\omega'^2} = \frac{f}{F} \approx \frac{3\, N^2}{20}.$$

The present accuracy of $y' = 0.02$ seconds $\approx 2 \times 10^{-7}$ days, $\omega' = 10^{-8}$, gives $N \approx 52$ days. For periods much longer than 2 months the error is due chiefly to the error in the rate of the clock. For much shorter periods the error is due chiefly to the error in astronomic time determination, and equals

$$m' = \frac{y'}{\sqrt{2\,F}} \frac{\sqrt{12}\, y'}{N^{3/2}},$$

where the approximation holds for all but very small values of N. The chief limitation at present is imposed by the astronomic time determination rather than by the clock.

Conclusions

In fig. 2 the probable error in the mination of the anomalies in the earth tion has been plotted against the le time over which the average has been The lines correspond to the four possibl binations between astronomic time dete tion (p.e. of present method 0.02 sec, of graphic zenith telescope 0.002 sec) and ard time determination (p.e. of crystal $1:10^8$, of cesium clock $1:10^9$). Accor fig. 2 the probable error of monthly a now is 5×10^{-9}. The probable error of S measurements, judged externally fro consistency of his observations, is son smaller, and our values for the accu astronomic time determination and the tube can be regarded as conservative.

The shaded band in fig. 2 is an esti the desirable accuracy. For exampl measurement of seasonal variations c

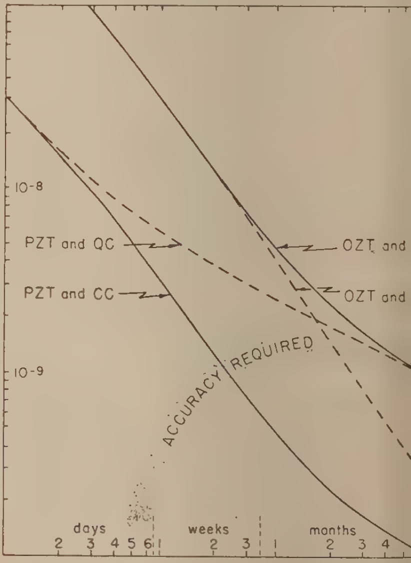

Fig. 2. Probable fractional errors in determi earth's angular velocity as a function of the l time over which the measurement of the velo averaged. The four lines correspond to the combinations of the ordinary zenith tube n (OZT, ± .02 sec.), and the proposed phot zenith telescope (PZT, ± .002 sec.), with th clock (QC, $\pm 10^{-8}$), and the proposed cesiu (CC, $\pm 10^{-9}$). The shaded band is an estima largest probable error permissible for determin tuations in the earth's rotation of given d

hundred million requires monthly
st quarterly) values accurate to, say,
per billion. The present accuracy is
too small for a reliable measurement
ariations, but not too small for their

r to study fluctuations of annual
ofar as they are related to meteoro-
nditions it will be necessary to im-
accuracy of the clock, and further-
refer to an absolute time standard.
uirements are fulfilled by the ce-
k.

lies persisting for short periods of
be relatively small, and the required
orrespondingly high. Since the "half
mospheric circulation is only a week
expect anomalies persisting for a
be as large as perhaps 25 per cent of
hly anomalies. The required accuracy
can then be set at one part in two billion. According to fig. 2 the development of the photographic zenith tube and of the cesium clock should enable us to measure anomalies persisting for two weeks or more. By relaxing our requirements and assumptions these values can be improved by a factor of two. Any further improvement will depend largely upon our ability to correct the astronomic time determination during zenith passage for the refraction of light from a distant star by the atmosphere directly over the telescope. Thus the ultimate limitation on measuring atmospheric circulation by this method is imposed by the atmosphere itself. It is hoped that the great interest attached to an index of *integrated* circulation as derived from anomalies in the earth's rotation might provide an additional incentive to improve present methods of time determination.

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SUBMARINE TOPOGRAPHY AND SEDIMENTATION IN THE VICINITY OF MUGU SUBMARINE CANYON, CALIFORNIA

TECHNICAL MEMORANDUM NO. 19
BEACH EROSION BOARD
CORPS OF ENGINEERS

JULY, 1950

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FOREWORD

This paper was prepared by D. L. Inman of the University of California. The report appeared in limited issue as Submarine Geology Report No. 10 of the Scripps Institution of Oceanography, Scripps Contribution No. 473, University of California. It is believed that the results of the investigations outlined herein are of sufficient value to merit publication at this time.

The opinions and conclusions expressed by the authors are not necessarily those of the Board.

The authority for publication of this report was granted by an act for the improvement and protection of beaches along the shores of the United States, Public Law No. 166, 79th Congress, approved July 31, 1945.

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SUBMARINE TOPOGRAPHY AND SEDIMENTATION IN THE VICINITY OF MUGU SUBMARINE CANYON, CALIFORNIA

Abstract

Mugu Submarine Canyon resembles the subaerially eroded canyons inland except that the two branches at its head are somewhat unusual in having an isolated ridge protruding from the floor of each branch and parallel to the canyon axis. Cores indicate that there are hard rock outcrops at several points on the floor along the deeper portions of the canyon. The maximum gradient of the canyon occurs at its two heads and may represent the maximum angle of repose of recent fill. There are indications that the heads and sides of the submarine canyon are relatively unstable as compared to the more gently sloping shelf areas on either side of the canyon.

The sediments on the shelf areas adjacent to the canyon show a somewhat systematic variation in type; however, the distribution of sediments from the floor and sides of the canyon is complex and not a function of depth. Analysis of the samples shows that the upper canyon sediments are poorly sorted and have an asymmetrical size distribution which differs from the well sorted and more symmetrical shelf sediments.

Introduction

Between December 1948 and April 1949 a series of investigations were made of the beaches in the vicinity of Mugu Lagoon, California, and of the bottom topography and sediments of the adjacent sea floor. The beach study (Inman, 1950) was concerned with the transport of sand by waves and longshore currents, and the effects of waves and tidal action on the stability of the narrow sand spits at the mouth of Mugu Lagoon. The present paper is primarily concerned with the bathymetry of the shelf, the submarine canyon heads adjacent to the beach and lagoon, and the relation of sediment type of bottom topography.

Beach samples were obtained on 18-19 December 1948 and 8 January 1949. A portion of the shallow water surveying and sampling was done on 8 January 1949 in an AVR (air-sea rescue craft) provided by the Navy, and equipped with an NK-6 portable echo sounding device. The remainder of the surveying, the dredging, coring, and deeper grab sampling were conducted during 22-24 April 1949 from the 105 foot research vessel, E. W. SCRIPPS, of the Scripps Institution of Oceanography. In addition to the samples collected in 1948 and 1949, the locations and mechanical analyses of twelve cores and dredge hauls obtained in the area by Dr. F. P. Shepard in 1938 are included. The mechanical analyses of these earlier samples were made by Dr. Roger Revelle.

Acknowledgments

I wish to thank Dr. F. P. Shepard of Scripps Institution of Oceanography for his field work and many helpful suggestions; Doctors M. W. Johnson, W. R. Coe, and J. L. Baily for the identification of the macrofauna; Miss Frances L. Parker for the identification of foraminifera; Dr. Roger Revelle for critical reading of the manuscript; Messers. D. M. Poole and W. S. Butcher for assistance in the mechanical and optical analyses of the sediments; and Mr. D. B. Sayner and Miss Ruth Yound for field and laboratory assistance. I am indebted to the U. S. Navy for the use of an air-sea rescue craft, and to the U. S. Navy and the Parsons Aerojet Company of Los Angeles for range markers for the survey, and for the opportunity to make this study.

Description of the Area

The shelf area under discussion is on the open coast at the head of Mugu Submarine Canyon, and is just offshore from Mugu Lagoon and Point Mugu, California (Figure 1, insert). The area extends for approximately three nautical miles along the coast and one mile offshore, and is located nine miles southeast of Oxnard and 40 miles west of Los Angeles, California.

The continental shelf is approximately nine miles wide off the city of Ventura, and narrows progressively to one mile in the vicinity of Point Mugu. The submarine contours along the shelf are essentially parallel except where interrupted by a few submarine canyons. The two largest canyons, Hueneme and Mugu, traverse the continental shelf and extend shoreward to the beach. Mugu Submarine Canyon is located just seaward of Mugu Lagoon and extends for nine miles in a southerly direction where it enters Santa Monica submarine basin.

Point Mugu forms the southeast boundary of the Oxnard plain which borders the coast from Ventura to Point Mugu. The Oxnard plain extends for 17 miles along the coast and lies between the Santa Ynez and the Santa Monica mountain ranges. It extends inland for approximately eight miles and has an average elevation of about 30 feet. The plain is bordered on the north by the Ventura River, and is traversed by the Santa Clara River and Calleguas Creek. The landward portions of the plain are formed from flood deposits of the latter two streams. Mugu Lagoon is a shallow tidal lagoon, extending four miles parallel to the coast immediately west of Point Mugu, and at the mouth of Calleguas Creek.

Point Mugu is a prominent headland of resistant black shales of the Vaqueros formation of Miocene age. There are no hard rock outcrops in the coastal region between Point Mugu and Ventura. Early Pleistocene conglomerates of the Saugus formation outcrop on the beach one mile west of Ventura (Putnam, 1942). These conglomerates dip steeply to the south.

Both the Santa Ynez Range (Putnam, 1942) and the Santa Monica Mountains (Davis, 1933) show extensive Pleistocene marine terracing. The Oxnard plain between these two ranges is a structural basin of deposition in which a considerable thickness of sediments has accumulated throughout much of the Tertiary. In general, the alluvial fill of Recent to late Pleistocene age is about 500 feet thick and is composed of unconsolidated material varying from gravel to clay with the coarser material predominating (Kaplow, 1947). The alluvium lies unconformably on the San Pedro formation of early Pleistocene age. The latter formation consists of sand and gravel interbedded with layers of silt, and reflects a progressive change from marine to continental deposition (Poland, et al, 1948).

A new fresh water well just east of U. S. Highway 101 (Alt.) and northeast of Mugu Lagoon encountered a sediment fill of approximately 1,500 feet overlying the Miocene. The material from near the surface to a depth of 600 to 700 feet is a permeable sand.[1]

During recent geologic time, the Oxnard plain has been built progressively seaward by river and marine deposition. The sediments discharged by the rivers have tended to migrate to the southeast under the influence of longshore currents set up by the predominant westerly wave approach.

Topographic Surveys

The offshore area in the vicinity of Mugu Submarine Canyon was surveyed by the U. S. Coast and Geodetic Survey in 1856, 1878 and 1933.[2] The 1856 and 1933 surveys included the area near the heads of Mugu Canyon. The soundings from the earliest survey showed a 120 foot shoal bar extending southeast from Laguna Point and separating the inner and outer portions of Mugu Canyon (see Shepard, 1933, figure 8). The latest Coast and Geodetic survey shows features comparable to the present topography and had sufficient soundings to assure that no such bar existed in 1933. There is some doubt as to the accuracy of the 1856 soundings since the bar does not now exist and such features are not found in other submarine canyons.

The Army Engineers (1948) took four beach profiles in this area in 1938 and repeated them in 1948. Two of the profiles were on the shelf west of Laguna Point and extended perpendicular to the beach and to depths of 35 feet below mean lower low water. The other two were taken at the head of each branch of Mugu Canyon and extended to depths of 50 feet.

1. Mann, John F., U. S. Geological Survey, personal communication.

2. U. S. Coast and Geodetic Survey Hydrographic Sheets Nos. 554, 1403, and 5425.

The detailed topography of the two branches of Mugu Canyon shown in figure 2 was compiled primarily from surveys made from a U. S. Navy AVR and from the E. W. SCRIPPS. The soundings are based on the records of echo sounding devices, checked at frequent intervals by vertical casts. Positions were obtained by multiple sextant angles on markers erected over bench marks and other known points. The plotted positions of the soundings are shown by small dots in figure 2.

A comparison of the 1949 soundings with those of the Coast and Geodetic Survey of 1933 showed indications of considerable depth changes near the canyon heads where the bottom slopes are steep. Deepening was indicated near Mugu Pier, and shoaling near the lagoon channel entrance. The shoaling is probably the result of deposition of silt and sand brought seaward by currents from the lagoon during ebb tides.

Submarine Topography

In the vicinity of Point Mugu a narrow continental shelf lies between the mainland and the Santa Monica Submarine Basin (Figure 1). The basin is approximately 40 miles long and 20 miles wide and has a maximum depth of 3,078 feet.

A profile of the continental shelf (figure 4) taken 8,000 feet west of Mugu Pier, shows that the shelf is only two miles wide and that the transition from shelf to continental slope occurs at a depth of approximately 200 feet. The average slope of the shelf is 0.8 degrees. The continental slope has an average inclination of 5.3 degrees down to depths of 1,200 feet. The shelf is one mile wide off Point Mugu and as in the case of the shelf west of the point, the change in slope occurs at approximately 200 feet.

The shelf in this area is cut by two submarine canyons. Mugu, the largest canyon, traverses the continental shelf and extends shoreward to the beach. The second canyon parallels Mugu canyon and is approximately two nautical miles to the west. This second canyon cuts the outer portion of the shelf and terminates about one mile from the shore.

Mugu canyon has two branches; an east branch extends shoreward almost to the beach at a point 2,000 feet east of Mugu Pier, and a west branch extends in equally close to a point 1,000 feet west of the pier. The seaward portion of the canyon is sinuous and can be traced for at least nine miles, where it enters the Santa Monica Basin at a depth of 2,400 feet.

The two branches of Mugu Canyon are separated by an elliptical ridge (7 Fathom Ridge) with a shoal area of 40-foot depth. The heads of both branches of the canyon are much broader than the deeper portions of the canyon at their juncture. The branches are unusual in that each has a ridge portruding from the floor of the canyon and paralleling the canyon axis. The ridge in the west branch of the canyon is particularly impressive as it extends approximately 95 feet above the canyon floor which is at a depth of about 220 feet at that point. The ridge has a maximum slope of about 41 degrees on its west side. The main canyon walls on either side of the ridge have maximum slopes of about 35 degrees on the west and 46 degrees on the east. The ridge on the axis of the east canyon head is less pronounced than that in the west canyon. Also, the side walls of the east canyon head are less steep, averaging about 19 degrees on the west wall, and 16 on the east wall. Profiles of the Mugu Canyon heads are shown in Figure 3.

The sediment fill in the heads of both branches of the canyon has an average slope of 13 degrees between depths of 20 and 100 feet. For depths greater than 100 feet the slopes of the canyon floors decrease gradually reaching a slope of about 1.6 degrees where the two branches of the canyon join south of Seven Fathom Ridge, at a depth of about 300 feet.

South of Seven Fathom Ridge the course of the canyon is sinuous and the slope of the canyon floor changes somewhat from point to point. A maximum slope of about 9.4 degrees occurs at depths of 800 to 1,200 feet. At greater depths, the slope gradually decreases toward Santa Monica Basin.

Longitudinal profiles of Mugu Canyon and Calleguas Creek, the stream that drains into Mugu Lagoon, are shown in figure 4. Comparison of the different portions of the profiles shows that the slopes of the submarine canyon do not differ radically from those found on land.

Sediment Investigations

Field Methods. The majority of the 1949 offshore samples were obtained with the LaFond Dietz snapper (LaFond and Dietz, 1948) and the Scoopfish bottom sampler (Emery and Champion, 1948). The LaFond-Dietz snapper retains about 200 grams of sample and probably does not penetrate more than 5 cm. on a sandy silt bottom. All of the 8 January 1949 samples were obtained with the light weight Scoopfish bottom sampler, because there was no adequate winch on the AVR. The Scoopfish has a capacity of about 75 cc., and does not usually retrieve a sample greater than 60 grams dry weight. Snapper type samplers were used because the sediment study was primarily concerned with the type and areal distribution of the surface sediments.

In addition to the snapper type samples, cores were obtained with a modified Emery-Dietz (Emery and Dietz, 1941) gravity coring device. Four dredge hauls using the heavy rock dredge (Shepard, 1948, figure 10) were made in the vicinity of Seven Fathom Ridge and off the lagoon mouth. This dredge has a capacity of six cubic feet.

The beach samples were all taken from the beach foreshore about five feet above mean lower low water. The samples were taken by pressing a small glass sample jar into the surface of the sand. This method gave a uniform sample about five centimeters in diameter and four centimeters deep.

All of the samples are listed in Tables I and II and their location is shown in Figures 1 and 2. Samples having file numbers from 1 to 90 and the prefix "M" were taken in 1948-49; those with a prefix "F" were obtained by Dr. F. P. Shepard in 1938.[3] The latter samples represent dredge hauls and cores, predominantly from the deeper portions of the canyon and shelf, while the former are from the upper canyon and shelf area shown in figure 2. Samples having file numbers with the suffix "D" are heavy dredge samples, and those with "C" are cores. Numbers with no suffix letter are beach or snapper type samples and are thus essentially from the upper few centimeters of the sea floor.

Laboratory Methods. After drying, each sample was subjected to a preliminary examination under a binocular microscope. Such things as the relative amount of micaceous material, degree of rounding of the particles, abundance of foraminifera, and the organic content of the sample were noted.

From the mechanical analysis data a cumulative frequency curve was drawn for each sample on logarithmic probability paper (figure 10) and the median diameter and the first and third quartile measures were obtained from the curve. From these measures, Trask's (1932) coefficients of sorting and skewness were computed. The sorting coefficient is defined as

$$S_o = \sqrt{\frac{Q_1}{Q_3}}$$

and the skewness coefficient as

$$SK = \frac{Q_1 Q_3}{Md^2}$$

where Q_1 and Q_3 ($Q_1 > Q_3$) are the quartile measures and Md is the geometric median diameter.

Following the mechanical analysis, light and heavy mineral counts were made on selected samples, as well as a foraminiferal count of four of the offshore samples. Detailed descriptions of the mechanical analysis procedure and of the fauna are given in appendixes I and II respectively.

Description of the Samples. The degree of sphericity was fairly low in all mineral grain sizes, most grains being highly angular and having the appearance of freshly broken material under a 24 power binocular microscope. No accurate measure of the degree of sphericity or rounding of the grains was made; however, it was noted that there was no visual indication of rounding of grains having a diameter smaller than about 0.3 mm. in any of the samples. In general, some rounding

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[3] Since the "M" and "F" series samples do not overlap numerically, the prefixes are omitted from Figures 1 and 2, to avoid congestion.

was found in grains larger than 0.3 mm, the tendency towards rounding increasing with increasing grain size. No difference in the degree of rounding of comparable size grains was noted between the beach and offshore samples. The beach samples had a slightly higher percentage of rounded material because the samples were coarser. Little tendency towards rounding was noted in the lagoon samples, even though they had median diameters comparable to the beach sands.

The relative amount of micaceous or platy material in the samples varied a great deal. The beach and lagoon samples contined very little platy material, while the shelf and canyon samples contained larger percentages of this type of material. In general, samples from the ridges contained more platy material than the beach samples, but less than those on the open shelf. The predominance of platy material in the shelf samples relative to the beach is shown by the distribution of biotite in figure 5. Biotite constituted 22 to 25 per cent of the total heavy mineral content of shelf samples M65 and M71, while no more than 3 per cent was found in the beach samples. Also, muscovite, which as a rule is not retained in the heavy fraction of the bromoform split, constituted 18 per cent of the heavy fractions of sample M65 and 21 per cent of M71. Muscovite was not observed in the heavy fractions of the other samples.

A similar relationship between micaceous material and depth was observed in Monterey Bay, California, by Galliher (1935). He noted that micas were found in few places between the strandline and five or ten fathoms, and that micas were especially plentiful in sediments lying between 20 and 30 fathoms.

Microscopic examination of the samples indicated that the organism content was fairly low in all samples, the relative content being somewhat greater in the canyon and shelf samples than in the beach samples. Organic material consisted of terrestrial plant remains, shell fragments echinoid spines, foraminifera and some bryozoans. Terrestrial plant remains were observed in the canyon samples and in some shelf samples, particularly off the entrance to Mugu Lagoon (samples M78, M80, and M81)[4] and (samples M65, 66 and 67) from the West shelf. The percentage of shell fragments increased with increasing depth, reaching a maximum of about 10 per cent of the total weight of sample M75 at a depth of 153 feet. The organic content was low in the samples from Seven Fathom Ridge; but, the one sample from Twenty Fathom Ridge had numerous bryozoan skeletons.

Heavy and Light Mineral Composition

A heavy mineral count was made of ten of the samples; three samples from the beach, two snapper type samples from the west shelf (M65 and M71), two samples from the hydraulic dredging in Mugu Lagoon (M1D and M2D), one heavy dredge haul from the steep west bank of Seven Fathom Ridge (M51D), and a core from the head of each branch of Mugu Canyon (M55C and M59C). The beach samples, M5, M14, and M19, are from the beach foreshore and are located, respectively, nine-tenths of a mile west of Mugu Pier, four-tenths of a mile east of the pier,

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[4] Sample 81 was the only sample obtained which smelled strongly of hydrogen sulfide.

and one-tenth of a mile west of Point Mugu.[5] The locations of the other samples are shown in figure 2.

Since the samples analyzed represented several possible sedimentation environments and there was a large variance in their median diameters and sorting, the heavy mineral separation was made from the entire sample rather than from any specific size fraction (see Rubey, 1933). The standard procedure employing bromoform was used to seperate the minerals into heavy and light fractions. The heavy minerals were mounted in Canada Balsam for counting.

The results of the heavy mineral analysis are shown graphically in figure 5. An inspection of this figure shows that the percentage of hornblende is relatively high in all samples. The augite content was found to be fairly low in the beach and virtually absent from the offshore samples. No titaniferous augite was observed in any of the samples. Since titaniferous augite occurs in the volcanic rocks outcropping southeast of Point Mugu, its absence on the Mugu beaches was used by the Army Engineers (1948) to indicate that there is no north west transport of sand around Point Mugu. Biotitle constitutes a relatively low percentage (2 to 5%) of the beach and lagoon samples, but increases to 22 and 25% in the open shelf samples. Biotite content of the cores in intermediate between that of the beach and the shelf samples. Zircon is virtually absent in the beach samples and increases to 2 to 5% in the shelf samples. It is low in the lagoon, and relatively higher in some portions of the cores. The greater abundance of zircon in the offshore samples may be due to its smaller diameter. Epidote is low in the beach and offshore samples and higher in the lagoon samples and the upper portions of the cores. Glaucophane was not found in the beach and lagoon samples but was found in the offshore samples, particularly in the dredge haul from the bank of Seven Fathom Ridge (sample M51D) and the lower portions of the two canyon cores.

In addition to the heavy minerals listed in figure 5, minor percentages of hypersthene, diopside, enstatite, chlorite, zoisite, basaltine, termolite, and clinozoisite were observed in the samples.

A count was made of the light mineral fractions of beach sample M5, shelf sample M71 and lagoon sample M2D. In all three samples, quartz was found to be the predominant light mineral, averaging about 75 per cent of the light fraction; while potash and plagioclase feldspars, and kaolin constitured the remaining 25 per cent.

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[5] Army Engineers (1948, Appen. 3, Plate 4) made heavy mineral counts of beach samples from Ventura to the Mugu area. Their samples nos. 25, 26, and 28 were from approx. the same locations as samples M5, M14, and M19 of this report.

An abundant blue mineral was observed in the light fraction of sample M51D from the side of Seven Fathom Ridge. The mineral is thought to be vivianite,[6] a hydrous ferrous phosphate. The mineral occurs at irregularly spaced points as a blue impregnation of the clayey silt matrix of the sample. Occasionally it occurs as impregnation around a small vug, or as small ovoids. The maximum size of impregnation is about 2 or 3 cubic millimeters. The mineral is a deep blue color, has a powder blue streak, a hardness between 1.5 and 2.0 and a fusibility of about 2.0.. Mineral fragments are prismatic with one good cleavage, positive angle, indices 1.59 to 1.63, and strong bireferingence. Some grains appear to be microcrystalline. Fragments are transparent and have a blue to yellow pleochroism. The mineral is soluble in nitric acid, gives a positive test for phosphate with ammonium molybdate, and a positive test for iron with potassium thio cyanate.

Distribution of Sediments

The distribution of the medium diameters of the snapper type bottom samples is given in Figure 6. Inspection of this figure shows that the sediments do not show a uniform decrease in median diameter with increasing depth. However, it should be noted that the offshore samples were obtained during two different periods, so that they may not give a synoptic picture of the sediment distribution.

The beaches in the Mugu area are composed of a medium sand with an average median diameter of about 0.3 mm. The sandy portion of Mugu Lagoon near the lagoon entrance has about the same median diameter as the beach sands. Seaward of the beaches, the bottom sediments on the shelf grade rapidly into fine silty sand and sandy silt. The bottom material at a depth of 35 feet off the lagoon entrance has a median diameter of about 0.16 mm. and is somewhat coarser than material at comparable depths on the shelf west of the canyon, where the median is about 0.06 mm. The relatively coarse material off the lagoon mouth is probably the result of strong ebb tide currents transporting lagoon material seaward. Further evidence for this occurrence is suggested by the relationship of the sorting and skewness of the sediment to median diameter, which is discussed later in the paper.

Four dredge hauls were made in the area near Seven Fathom Ridge (figure 2, samples M49D, M50D, M51D, and M82D). The two from the top of Seven Fathom Ridge and one from the canyon wall off the lagoon entrance showed material similar to that obtained with snapper type bottom samples in the same areas. However, dredge M51D from the steep west side of Seven Fathom Ridge was quite different from other sediments obtained in the area. The material in this sample consisted

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[6] Hawkins (1945) found vivianite and glauconite filling fossil shells in the Tartiary sands of New Jersey. Reiche (1945) describes the occurrence of vivianite in the zone of weathering as the result of oxidation (aided by bacterial action) of the phosphates in the tissue and supporting members of organisms; the occurrence of an amorphous form of vivianite as the result of progressive desiccation of gels and coagels of phosphates and iron as in the case of drained alluvial deposits.

of a massive, homogeneous, compact, clayey silt with very little water content. Large pieces of the material, a foot or so in diameter showed no indication of stratification when broken open aboard ship. The material had a median diameter of 0.016 mm. and was much finer than material obtained on the ridge above or on the canyon floor below. Sediment on Seven Fathom Ridge had a median diameter of about 0.08 mm. and the sediment on the canyon floor below had median diameters ranging from 0.12 to 0.04 mm. Worm borings and cracks in the massive clayey silt were filled with sand size material similar to that found on Seven Fathom Ridge. The presence of vivianite (described under Mineral Composition) in this sample, the worm borings and cracks filled with sand, and the massive character and fine grain size of the material suggest that this material is an outcrop on the wall of Seven Fathom Ridge and has no relation to present day deposition. This suggestion is strengthened by an inspection of the relationship of sorting and skewness to the median diameter of sample M51D as compared to other samples in the area (see next section for discussion). Plots of this type for sample M51D indicate little relation between it and other samples from similar distances from shore (compared with samples M59D, M50D, M52, M59C, etc.). However, it agrees quite well with samples F117C, F118D, and F124D which are farther from shore and from greater depths. The only sample obtained near M51D which resembles it in sediment type, is the lower consolidated portion (19 to 41 cm) of core M55C from the side of the ridge in the west canyon (figure 2).

Inspection of figures 3, 6, and 7 shows that the distribution of bottom sediments in Mugu Canyon and its branches is complex and not a function of depth. Sediments on the steep slopes at the heads of the canyon have a median diameter of about 0.08 mm. The average slope of about 13 degrees at the canyon heads probably represents the maximum angle of repose of this size material. Similar gradients for this type material are found in the heads of La Jolla Submarine Canyon near La Jolla, California.

Snapper type samples (figure 6) from the upper portions of Mugu Canyon consist of material ranging in median diameter from about 0.12 to 0.04 mm. On the other hand the upper 27 cm. of a 30 cm. core (M62C) taken at a depth of 480 feet on the axis of Mugu Canyon graded from fine sand at the top, through medium and coarse sand to pebbles with a maximum diameter of 25 mm. (figure 7B). The bottom 3 centimeters underlying the pebbles consisted of granules in a matrix of clayey silt. Traces of fine sand were found near the juncture of the two branches of Mugu Canyon (M53C). The cores obtained in the branches of Mugu Canyon (M55C, M57C and M59C) had an average median diameter of about 0.04 mm. With the exception of the marked discontinuity in the mid section of core M55C and the bottom of core M62C, all of the canyon cores showed an increase in median diameter with increasing depth in the core (Figure 7A-B).

Two cores (Figure 1, F305C and F122C) taken on the axis of Mugu Canyon at depths of 930 and 1,656 feet gave evidence of hard bottom. In both cases the core nose was smashed; six pieces of angular gray sandstone cemented with chlorite and calcite were retained in the barrel of core F305C, and traces of sand were found on the barrel of core F122C. Core M89C from a depth of 1,458 feet on the canyon axis between cores F305C and F122C was silt. The sandstone obtained in Core F305C is apparently from an outcrop in the canyon floor (Emery and Shepard, 1945). At that depth, the canyon has a maximum gradient of 9.4 degrees as compared to a gradient of 3.3 degrees above and 2.7 degrees below the area (see figure 4). Only one core was obtained in the large canyon west of Mugu Canyon. This core, F304C, was a silt core, 183 cm. long, and was obtained from the canyon axis at a depth of 876 feet.

Two hauls with the heavy dredge (Figure 1, F121D and F123D) from the sides of the deeper portions of Mugu Canyon at depths of 840 and 1,470 feet showed that the sides of the canyon consist of clayey silt. Two dredge hauls from the top of 47 Fathom Ridge (figure 1, F125D and F126D) showed that the ridge is covered by large pieces of crystalline limestone and chert and a few shells. The rocks were washed clean and no mud or sand was found except in the cracks in the rocks. Emery and Shepard (1945) suggest that the limestone and chert represent Miocene outcrops. A dredge from the side of 47 Fathom Ridge (F124D) contained silt with small pieces of cherty shale and limestone.

Samples 3 through 90 (shown on figure 2) from the shelf and upper canyon, with the exception of M51D and core M62C, appear to represent modern sediments and to be the result of transportation and deposition under present day environmental conditions.

The depth of overburden of the modern sediments is not known, as no hard rock outcrops were found in the area of the shelf or upper canyon. The steepness of the canyon walls, and the character of the material composing the west bank of Seven Fathom Ridge (M51D), suggest that the depth of overburden of the modern sediments may not be great except at the canyon heads and off the lagoon channel entrance. Comparisons of recent surveys (Inman, 1949a) indicate a fill off the lagoon entrance and large changes along the steep portions near the heads of the canyon.

In 1929, two jet borings in Hueneme Submarine Canyon (Shepard and Emery, 1941, p. 88) showed that the recent fill at the head of the canyon in water 28 and 40 feet deep is at least 40 feet thick. A boring in water 20 feet deep encountered 26 feet of recent fill overlying rocks and boulders.

Relation of Sediment Type to Topographic Environment

The median diameters and Trask coefficients of sorting and skewness of the samples were investigated to see if these constants which are based on mechanical analysis of the sediments would show a relationship to the various topographic environments in the Mugu area.

It has been shown (Inman, 1949) that sorting and skewness of sediments are dependent somewhat on the size of the sediments; those having median diameters near 0.18 mm. being better sorted and having a more symmetrical size distribution under similar conditions of transportation and deposition than coarser or finer sediments. Thus it is to be expected that sediments from the same or similar environments may differ widely in their degree of sorting and skewness if they differ in median diameter. A comparison of the sorting and skewness of sediments may be meaningless from the standpoint of transportation and deposition unless the median of the samples is also considered.

Figure 8 shows the sorting and skewness of all the samples, including cores and dredge hauls, plotted as a function of median diameter. This figure shows that sediments with a median diameter near 0.2 mm. tend to be better sorted and have a more symmetrical size distribution than coarser or finer sediments. The figure also shows that there is a rather wide range in the sorting and skewness of samples having similar median diameters.

Figure 9A shows data similar to that given in figure 8, only in this case symbols are used to represent each of the several topographic environments. With the exception of the lagoon samples, this figure includes only beach samples and bottom sediments obtained with the snapper type sampler. Cores and dredge samples were excluded because they would not necessarily give a synoptic picture of the sedimentary processes. It was felt that an unduly large sampling error would be introduced if sampling techniques differing as widely as snappers, cores and dredges were compared on an equal basis. However, dredge samples M1D and M2D were included because they were the only samples available from the lagoon.

An inspection of figure 9 shows that in all but one case (sample M75) the open shelf sediments differ from the canyon sediments of comparable median diameters. Sample M75, which was grouped with the open shelf samples, plots with the canyon samples. This sample was obtained on the west shelf at a depth of 153 feet near the break in slope at the head of the large canyon west of Mugu Canyon (figure 1). Although it was the deepest and farthest from land of the shelf samples, only seven shelf samples are coarser and these were all taken in shallow water near shore. Sample M75 also has a higher percentage of shell fragments than other shelf samples.

It was found that the beach samples graded into the samples from the west shelf (solid line, figure 9A), but that samples from the sandy portion of the shelf off the lagoon mouth were coarser than samples of comparable depth and more poorly sorted than samples of comparable median diameter from the west shelf. The discrepancy in sorting between the samples off the lagoon mouth and those on the west shelf was most pronounced for samples nearest the lagoon. It may be that the relatively poor sorting of samples near the lagoon mouth is the result of fairly rapid deposition of lagoon material by strong ebb tide currents flowing from Mugu Lagoon.

Plots of the sorting and skewness against median diameter for the snapper type samples from 7 Fathom Ridge fall intermediate between the canyon and the shelf sediments. The only sample from 20 Fathom Ridge M90, plots among the canyon samples.

In order to show the relation between sorting and skewness and median diameter in a single curve, the data shown in figure 9A is replotted in figure 9B using the ratio of the sorting coefficient to the skewness coefficient (So/Sk). This method of representation avoids the use of two curves and, in the case of the Mugu sediments, gives a wider separation to the various sediment types.

There is no apparent reason why the samples from 7 Fathom Ridge should fall intermediate between the shelf and the canyon samples. However, it seems reasonable that the shelf samples should differ from the canyon samples. The canyon and the open shelf differ as a sedimentation environment both in the quantity or rate of sedimentation and in the nature of the currents that transport and sort the material. Investigations in this and other areas where detailed studies of submarine canyons have been made indicate that where canyons head near shore, the area near the canyon heads is subject to relatively rapid deposition followed by slumping of the material into the canyon (Shepard, unpublished data).

Probably the most effective sorting agent in the nearshore environment is the periodic onshore and offshore orbital motion associated with shallow water waves. This sorting agent is one that decreases in intensity with increasing depth and distance from shore, and over a narrow shelf such as that west of Mugu Canyon it probably results in a gradually decreasing but continuous agitation from the surf zone to near the break in slope at the outer shelf. In contrast to the shelves, the deep water and the wave divergence over the canyon result in a minimum of orbital motion on the canyon floors.

Little is known regarding other types of current action that occur on the shelves or in submarine canyons. Some current measurements have been made with Ekman type meters on the shelves and in the canyons off both coasts of the United States. Shepard, Revelle and Dietz (1939) found that the maximum currents in deep water were comparable to those in shallow water. They suggested that the currents were due to large moving eddies with vertical axes. Shepard (1949), in describing diving operations in La Jolla Submarine Canyon, found no evidence of significant density currents nor of any strong currents on the canyon floors. He attributed turbidity in the canyon heads in part to the settling of mud carried out over the canyons by rip currents. Shepard suggested that the slow up and down motion observed on the canyon floors may be associated with "surf beat" (Munk, 1949), which is a shallow water wave having the period of the grouping between high waves in the surf zone.

From the foregoing discussion it is to be expected that canyon sediments will be more poorly sorted than shelf sediments because they receive both beach and shelf material and because the steep canyon slopes minimize both local and progressive sorting. Also in contrast to the open shelf, deep water in the canyon heads allows a greater percentage of fine material to gravitate to the canyon floor. The addition of fine material is indicated by the pronounced asymmetry in the cumulative frequency curves of the canyon sediments. Two open shelf and two canyon samples having similar median diameters are compared in figure 10. Both the poor sorting and asymmetry caused by the addition of fine material in the canyon samples are shown graphically in this figure. It will be noted that the canyon samples include material both coarser and finer than shelf samples of comparable median diameter.

In conclusion it may be stated that in the Mugu area it is possible to distinguish between the canyon and the west shelf sediments on the basis of their mechanical analyses (figures 9A and 9B). However, a single sediment sample from any given environment may be misleading; a suite of samples is required before any peculiarities in sediment type can be established as diagnostic of a given environment.

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APPENDIX I - MECHANICAL ANALYSIS

All of the "M" series samples were air-dried, then crushed with a rubber pestle, and a Jones Splitter was used to obtain a test sample of about 25 grams. The test sample was soaked overnite in a 0.05 normal solution of sodium hexametaphosphate, then wet-sieved through a 0.0625 mm. mesh sieve to separate the sand fraction from the silt. The pipette method was used to analyse the fine fraction. The coarse fraction was dried, weighed and then dry-sieved through a 1.0 mm. mesh sieve. The sand size material between 1.0 and 0.0625 mm was analyzed with the Emery Settling Tube (Emery, 1938). The fraction greater than 1.0 mm. and the results from the settling tube were combined with the pipette analysis of the finer fraction into a single table of percentages.

Sodium hexametaphosphate was used as a peptizing agent in the pipette analysis rather than sodium oxalate, because flocculation was observed in some analyses using the oxalate method. Flocculation with sodium oxalate may have resulted from drying the samples before the analysis. Sodium hexametaphosphate was found to be superior to sodium oxalate for dispersing the dried sediments.

The Emery settling tube was used in the mechanical analysis of the 1.0 to 0.0625 mm. fraction, because: (1) it was felt that the equivalent diameters (Sverdrup et al, 1942, p. 958) obtained by this method are more significant in terms of sediment transportation and deposition than the weight-size distribution obtained by the more common method of sieving; (2) since the pipette analysis of the fine fraction is based on the equivalent diameters of the sedimentary particles rather than on their size, it seemed advisable to use a similar procedure such as the settling tube in analyzing the coarse fraction; and (3) the settling tube method does not restrict the divisions in the size analysis to Wentworth or $\sqrt{2}$ units, but allows the number of points and the diameters to be selected so as to give information at critical points in the size distribution of the sample. This is particularly helpful in the analysis of well sorted beach sand, a case in which sieving usually gives too few points to draw an accurage cumulative frequency curve.

Emery (1938) showed that the mechanical analysis of sand obtained by the settling tube method was in good agreement with analysis based on sieving when the material was spherical quartz sand; however, when appreciable amounts of heavy minerals or platy material such as mica are present, analysis by the two methods gives somewhat different results. The settling tube gives an equivalent diameter that is based on the settling velocity of the material, regardless of its specific gravity and shape so that it seems probable that this method gives a more representative distribution relative to the mechanics of sediment transport.

Recent investigations at Scripps Institution of Oceanography (Poole and Butcher, 1950), indicate that the probable error in median diameter resulting from repeated analysis of the same sample by the settling tube is comparable to that obtained by sieving, and amounts to about 0.8 per cent. The total probable laboratory error in the analysis of the sand size portions of the samples does not exceed about 3.0 per cent.

There was some question as to whether organic material such as shells and shell fragments should be included in the mechanical analysis of samples. If the material was predominantly fragmentary and showed a fairly regular size distribution, it was included in the analysis. Whole shells and large fragments were as a rule excluded from the analysis.

APPENDIX II - FAUNA

The macrofauna found in the samples are listed in Table III. The shells listed under sample M2D from the lagoon were obtained at the pipe outlet of a hydraulic dredge operating in the lagoon. At that time material was being dredged from about 5 to 15 feet below the bottom of the lagoon, and supposedly represented material deposited at an early stage of the lagoon. Since no living forms were observed while collecting the shells, it is assumed that all of the material was from below the bottom of the lagoon and not due to slumping from the sides of the dredge area. Living specimens of all except Saxidomus giganteus and Sinum debile were collected from Mugu Lagoon by Dr. M. W. Johnson in November of 1937. Saxidomus giganteus is a cool water species, and living specimens apparently do not occur south of Monterey Bay (Grant and Gale, 1931).

The living fauna obtained in two of the dredge hauls are listed in Table III. The two small gastropods found in cores M57C and M62C may be pre-Recent, although their species are found in modern assemblages.

Foraminifera: Samples 1 through 90 were given a cursory examination for foraminifera. The foraminiferal content was very sparse in all samples, and virtually absent from the samples from the beach and lagoon. A detailed foraminiferal count was made of samples M47, M51D, M52, and M69, which were from the top and side of Seven Fathom Ridge, the bottom of the west canyon head, and the wall of Mugu Canyon respectively. The foraminiferal count for these samples is given in Table IV.

The foraminifera from samples M47, M52, and M69 were obtained from 20 to 25 grams of sample. The foraminifera in M51D were obtained from approximately 130 grams of sample. All of the samples were characterized by a relatively high percentage of Buliminella elegantissima, which is one of the forams characterizing Nathland's (1933) temperature-depth Zone II, which includes temperatures ranging from 13.2 to 21.4°C. and depths of 14 to 125 feet. The foraminiferal assemblage of sample M51D, which was taken from the steep side of Seven Fathom Ridge, was quite similar to the other samples in its predominant shallow water assemblage. It differed from the others in the assemblage of less abundant species, and having an unusually low concentration of foraminifera.

TABLE I. LAGOON AND BEACH SAMPLES IN VICINITY OF MUGU LAGOON

Sample File No.	SIO Date No.	General Location[4]	Md (in mm.)	So	Sk	$\log_{10}$ Sk	Foreshore Slope
		Lagoon Samples					
M 1D	1 Dec. 48-1	Dredged from Mugu Lagoon	.345	1.55	.96	-.018	
M 2D	18 Dec. 48-3f	Dredged from Mugu Lagoon	.230	1.45	1.04	+.017	
		Beach Samples					
M 3	18 Dec. 48-1	Beach foreshore (6700' West of Mugu Pier)	.338	1.26	1.15	+.061	5.2°
M 4	18 Dec. 48-1a	Beach foreshore (6300' West of Mugu Pier)	.310	1.22	1.07	+.029	5.4°
M 5	18 Dec. 48-1b	Beach foreshore (5700' West of Mugu Pier)	.300	1.22	1.08	+.033	5.1°
M 6	18 Dec. 48-1c	Beach foreshore (4900' West of Mugu Pier)	.320	1.27	1.16	+.064	5.1°
M 7	18 Dec. 48-2	Beach foreshore (3800' West of Mugu Pier)	.293	1.24	1.10	+.041	4.9°
M 8	18 Dec. 48-2a	Beach foreshore (2900' West of Pier Near B.M. Estera)	.308	1.24	1.09	+.037	5.4°
M 9	18 Dec. 48-2c	Beach foreshore (1800' West of Mugu Pier)	.230	1.16	1.04	+.017	1.5°
M10	18 Dec. 48-"0"	Beach foreshore (at Mugu Pier)	.375	1.31	1.09	+.037	4.1°
M11	18 Dec. 48-3a	Beach foreshore (900' East of Mugu Pier)	.240	1.21	1.08	+.033	4.3°
M12	18 Dec. 48-3b	Beach foreshore (1400' East of Mugu Pier)	.255	1.31	1.16	+.064	4.3°

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[4] All beach samples taken at approximately 5 feet above Mean Lower Low Water.

TABLE I (continued)

Sample File No.	SIO Date No.	General Location[4]	Md	So	Sk	$\log_{10}$Sk	Foreshore Slope
M13	18 Dec. 48-3c	Beach foreshore (1800' East of Mugu Pier)	.310	1.40	1.03	+.013	5.2°
M14	18 Dec. 48-3d	Beach foreshore (2400' East of Mugu Pier)	.310	1.28	1.07	+.029	4.9°
M15	18 Dec. 48-3e	Beach foreshore (3100' East of Mugu Pier)	.425	1.31	1.03	+.013	3.9°
M15a	18 Dec. 48-3e-1	Beach foreshore (3100' East of Mugu Pier. Taken 5-10 cm below surface.)	.770	2.54	1.16	+.064	
M16	19 Dec. 48-4a	Beach foreshore (4700' East of Mugu Pier)	.290	1.24	1.06	+.025	3.2°
M17	19 Dec. 48-4b	Beach foreshore (5100' East of Mugu Pier)	.310	1.25	1.13	+.053	3.2°
M18	19 Dec. 48-4c	Beach foreshore (8500' East of Mugu Pier)	.320	1.26	1.04	+.017	3.5°
M19	19 Dec. 48-4d	Beach foreshore (11,100' East of Mugu Pier)	.360	1.35	1.10	+.041	4.8°
M20	8 Jan. 49-1B	Beach foreshore (900' West of Mugu Pier)	.230	1.20	1.03	+.013	4.3°
M 21	8 Jan. 49-2B	Beach foreshore (2400' East of Mugu Pier)	.312	1.24	1.16	+.064	2.6°
M22	8 Jan. 49-3B	Beach foreshore (2000' East of Mugu Pier)	.390	1.27	1.02	+.008	9.5°
M23	8 Jan. 49-4B	Beach foreshore (1700' East of Pier)	.440	1.34	1.08	+.033	8.6°

TABLE I (continued)

Sample File No.	SIO Date No.	General Location[4]	Md	So	Sk	$\log_{10}$Sk	Fore-shore Slope
M24	8 Jan. 49-5B	Beach foreshore (1400' East of Mugu Pier)	.320	1.30	1.03	+.013	6.9°
M25	8 Jan. 49-6B	Beach foreshore (1100' East of Mugu Pier)	.470	1.44	1.14	+.057	10.3°
M26	8 Jan. 49-7B	Beach foreshore (800' East of Mugu Pier)	.270	1.30	1.12	+.049	2.2°
M27	8 Jan. 49-8B	Beach foreshore (400' East of Mugu Pier)	.300	1.25	1.00	0	
M28	8 Jan. 49-11B	Beach foreshore (1500' West of Mugu Pier)	.320	1.27	1.11	+.045	5.6°
M29	8 Jan. 49-13B	Beach foreshore (2400' West of Mugu Pier)	.370	1.37	1.24	+.093	6.9°
M30	8 Jan. 49-14B	Beach foreshore (2800' West of Mugu Pier)	.376	1.33	1.13	+.053	8.6°
M31	8 Jan. 49-15B	Beach foreshore (3300' West of Mugu Pier near B.M. Estera)	.327	1.32	1.19	+.076	7.8°
M32	8 Jan. 49-16B	Beach foreshore (4000' West of Mugu Pier)	.320	1.33	1.18	+.072	8.2°

TABLE II. OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample In Feet[5]	Depth in Core (cm)	Md (in mm)	So	Sk	$\log_{10}$Sk
M33	8 Jan. 49-1	West shelf (off B.M. 8.70)	Scoopfish	46		.068	1.24	0.95	-.023
M34	8 Jan. 49-2	West Canyon head	Scoopfish	54		.089	1.45	0.81	-.092
M35	8 Jan. 49-3	7 fath. Ridge	Scoopfish	62		.060			
M36	8 Jan. 49-4	W. shelf (off B.M. Estera)	Scoopfish	10		.130	1.14	1.02	+.008
M37	8 Jan. 49-5	W. shelf (off B. M. Estera)	Scoopfish	19		.114	1.24	1.02	+.008
M38	8 Jan. 49-6	W. shelf (off B.M. Estera)	Scoopfish	32		.090	1.26	1.01	+.004
M39	8 Jan. 49-7	W. shelf (off B.M. Estera)	Scoopfish	38		.080	1.37	0.954	-.024
M40	8 Jan. 49-8	W. shelf (off B. M. Estera)	Scoopfish	48		.067			
M41	8 Jan. 49-9	W. shelf (off B.M. Estera)	Scoopfish	54		.060			
M42	8 Jan. 49-10	W. shelf (off B.M. Mag.)	Scoopfish	50		.061			
M43	8 Jan. 49-11	W. shelf (off B.M. Mag.)	Scoopfish	40		.067			
M44	8 Jan. 49-12	W. shelf (off B.M. Mag.)	Scoopfish	30		.064			

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[5] All depths referred to Mean Lower Low Water.

TABLE II. OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON (continued)

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample in Feet5/	Depth in Core (cm)	Md	So	Sk	Log$_{10}$Sk
M45	8 Jan 49-13	W. shelf (off B.M.Mag.)	Scoopfish	21		.096	1.25	1.00	-0
M46	22 Apr 49-1	7 Fathom Ridge	L.D.Snapper	40		.082	1.43	.797	-.098
M47	22 Apr 49-2	7 Fathom Ridge	L.D.Snapper	40		.073	1.38	.90	-.046
M48	22 Apr 49-3	7 Fathom Ridge	BT Sampler	48		.094	1.26	.965	-.015
M49D	22 Apr 49-4	7 Fathom Ridge	Heavy Dredge	102-40-75		.056	1.63	.880	-.055
						Dredge 1/2 full unconsol. grey sandy silt, no rocks. Fauna in Table III.			
M50D	22 Apr 49-5	7 Fathom Ridge	Heavy Dredge	42-41-120		.058	1.50	.82	-.085
						Dredge 1/4 full unconsol. grey sandy silt, no rocks. Fauna in Table III.			
M51D	22 Apr 49-6	7 Fathom Ridge (W. bank)	Heavy Dredge	127-75		.0164	3.60	.371	-.431
						Dredge full massive compact greenish grey clayey silt. Worm borings filled with sand.			
M52	23 Apr 49-8	West Canyon Head (axis)	Scoopfish	159		.079			

TABLE II. OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON (continued)

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample in Feet[5]	Depth in Core (cm)	Md	So	Sk	$\log_{10}$Sk
M53C	23 Apr. 49-9	West Canyon (axis)	Short Corer	277		(Trace of fine sand)			
M54	23 Apr. 49-10	West Canyon (axis)	Scoopfish	277		.115	1.79	.937	-.028
M55C	23 Apr. 49-11	West Canyon (E. axis)	Short Corer	190	0-19	.044	1.85	.715	-.146
					19-30	.017	3.60	.382	-.418
					30-41	.039	2.32	.514	-.289
						41 cm. core, upper 19 cm. unconsol. grey silt, lower portion compact greenish grey silt			
M56	23 Apr. 49-12	West Canyon (Ridge)	Scoopfish	180'		.042	2.39	.393	-.407
M57C	23 Apr. 49-13	East Canyon (E. axis)	Short Corer	275	0-2½	.030	2.67	.323	-.490
					2½-9	.040	2.00	.490	-.310
					9-21	.046	1.71	.793	-.100
						21 cm. core, unconsol. grey sandy silt. Fauna in Table III.			
M58	23 Apr. 49-14	East Canyon (E. axis)	Scoopfish	290		.045			
M59C	23 Apr. 49-15	East Canyon Head (W. axis)	Short Corer	133	0-10	.026	3.50	.290	-.538
					10-20	.037	2.34	.402	-.395
					20-30	.046	1.50	.713	-.147
						30 cm. core, unconsol. and wet throughout. Grey sandy silt.			
M60	23 Apr. 49-16	East Canyon Head	Scoopfish	141		.054	1.91	.662	-.179

TABLE II. OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON (continued)

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample in Feet5/	Depth in Core (cm)	Md	So	Sk	$\log_{10}Sk$
M61	23 Apr. 49-17	East Canyon Head	Scoopfish	78		.062	2.07	.583	-.234
M62C	23 Apr. 49-18	Mugu Canyon (axis)	Short Corer	480	0-10	.160	1.25	1.00	0
					10-20	.193	1.26	1.00	0
					20-25	.275	1.52	1.10	+.041
					25-27	Pebbles. Max. size 11 x 25 mm.			
					27-30	Granules in clayey silt matrix. 30 cm core, upper 27 cm. clean unconsol. sand and pebbles.			
M63	23 Apr. 49-19	Mugu Canyon (axis)	Scoopfish	470		.068	1.50	.600	-.210
M64	23 Apr. 49-20	East Canyon head (ridge)	Scoopfish	150		.065			
M65	23 Apr. 49-21	West Shelf (off B.M. Estera)	L. D. Snapper	38		.073	1.39	.946	-.024
M66	23 Apr. 49-22	West Shelf (off B.M. Estera)	Scoopfish	42		.064			
M67	23 Apr. 49-23	West Shelf (off B.M. Estera)	L.D. Snapper	53		.040	1.58	.770	-.113
M68	23 Apr. 49-24	West Shelf (off B.M. Estera)	L.D. Snapper	80		.046	1.37	.850	-.070
M69	23 Apr. 49-25	West Shelf (off B.M. Estera)	L.D. Snapper	330		.035	1.88	.635	-.198

TABLE II. OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON (continued)

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample in Feet[5]	Depth in Core (cm)	Md	So	Sk	$\log_{10}$Sk
M70	23 Apr. 49-26	West Shelf (off B.M. Dune)	L.D. Snapper	34		.059	1.26	.940	-.027
M71	23 Apr. 49-27	West Shelf (off B.M. Dune)	L.D. Snapper	48		.053	1.29	.941	-.026
M72A	23 Apr. 49-28A	West Shelf (off B.M. Dune)	L.D. Snapper	69		.056	1.38	.941	-.026
M72B	23 Apr. 49-28B	West Shelf (off B.M. Dune)	L.D. Snapper	69		.059	1.34	.906	-.043
M73	23 Apr. 49-29	West Shelf (off B.M. Dune)	L.D. Snapper	91		.047	1.35	.896	-.048
M74	23 Apr. 49-30	West Shelf (off B.M. Dune)	L.D. Snapper	115		.046	1.32	.918	-.037
M75	23 Apr. 49-31A	West Shelf (off B.M. Dune)	L.D. Snapper	153		.090	1.72	.813	-.090
M76	23 Apr. 49-33A	East Shelf (opposite Lagoon)	L.D. Snapper	34		.157	1.30	1.00	0
M77	23 Apr. 49-33B	East Shelf (opposite Lagoon)	Scoopfish	34		.165	1.30	1.00	0
M78	23 Apr. 49-34	East Shelf (opposite Lagoon channel)	L.D. Snapper	43		.074	1.39	.913	-.039

TABLE II. OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON (continued)

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample in Feet[5/]	Depth in Core (cm)	Md	So	Sk	$\log_{10}$ Sk
M79	23 Apr. 49-35	East Shelf (opposite Lagoon)	Scoopfish	47		.160	1.33	.970	-.013
M80	23 Apr. 49-36	East Shelf (opposite Lagoon)	Scoopfish	31		.130	1.28	1.05	+.021
M81	23 Apr. 49-37	East Shelf (opposite Lagoon)	Scoopfish	65		.045	1.55	.926	-.033
M82D	23 Apr. 49-38	Mugu Canyon (East Bank)	Large Dredge	196-34		.040	1.67	.761	-.118
M83	23 Apr. 49-39	West Shelf (near W. Canyon head)	L.D. Snapper	40		.068	1.42	.926	-.033
M84	23 Apr. 49-40	West Shelf (near West Canyon)	L.D. Snapper	37		.062	1.37	.956	-.020
M85	24 Apr. 49-41	West Shelf (West Bank)	L.D. Snapper	70		.045	1.50	.745	-.128
M86	24 Apr. 49-42A	West Shelf (West Bank)	L.D. Snapper	47		.062			
M87	24 Apr. 49-42B	West Shelf (near W. Canyon)	L.D. Snapper	47		.053	1.46	.940	-.028
M88	24 Apr. 49-44	7 Fath. Ridge	Scoopfish	41		.076	1.41	.857	-.067

TABLE II. OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON (continued)

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample in Feet5/	Depth in Core (cm)	Md	So	Sk	Log$_{10}$Sk
M89C	24 Apr 49-45	Mugu Canyon (Axis)	Short Corer	1458	0-4	.026	3.14	.394	-.404
						4 cm. core, very compact greenish grey silt.			
M90	24 Apr 49-48	20 Fathom Ridge	Scoopfish	138		.062	1.78	.792	-.101
F117C 7/	22 May 38 FPS 117	20 Fathom Ridge	Ekman Corer	252 (42 fath.)	0-1.5	.006	5.00	.306	-,514
					1.5-4	.021	2.98	.446	-.351
					4-10	.024	3.07	.408	-.389
					10-18	.023	3.22	.390	-.409
					18-25	.027	2.73	.437	-.359
					25-33	.053	2.02	.731	-.136
					33-41	.072	1.69	.791	-.102
						41 cm. core, penetration 167 cm. upper mobile layer oxidized brown.			
F118D	22 May 38 - FPS 118	South Bank of 20 Fath. Ridge (Mugu Canyon Wall)	Large Dredge	1260-510 (210-85 fathom)		.035	2.30	.685	-.164
						Dredge full of very stiff green to black silt. Material oxidized for 1½ cm. below surface, and in holes.			
F119C	22 May 38 - FPS 119	South Bank of 20 Fath. Ridge (Mugu Canyon Wall)	Varney-Redvine Corer	912 (152 fath.)	0-22 22-25	Coring tube bent; 25 cm core Green mud One 5 c. freshly broken piece of grey sandstone with calcite cement.6/			

6/ Described in Emery and Shepard (1945).
7/ Mechanical analysis of "F" series samples made by Dr. Roger Revelle.

TABLE II. OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON (continued)

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample in Feet[5]	Depth in Core (cm)	Md	So	Sk	Log$_{10}$Sk
F120C	22 May 38 - FPS 120	South Bank of 20 Fath. Ridge (Mugu Canyon Wall)	Ekman Corer	480 (80 fath.)	0-1.5	.014	3.72	.508	-.294
					1.5-5	.027	2.59	.540	-.268
					5-13	.039	2.18	.681	-.167
					13-20	.045	1.79	.650	-.187
					20-28	.028	2.80	.720	-.143
					28-36	.030	1.92	.593	-.226
						36 cm. core, 137 cm. penetration. Greenish color.			
F121D	22 May 38 - FPS 121	West Bank, Mugu Canyon	Large Dredge	960-720 (160-120) fathom		.020	2.94	.428	-.369
						Green silt.			
F122C	22 May 38 - FPS 122	Mugu Canyon Axis	Ekman Corer	1656 (276 fathom)		Apparently hit rock, as tube bent and some sand on core barrel.			
F123D	22 May 38 - FPS 123	Mugu Canyon near axis	Large Dredge	1500-1440 (250-240 fathom)		Mud only.			
F124D	23 May 38 - FPS 124	Side of 47 Fathom Ridge	Large Dredge	1080-816 (180-136 fathom)		.033	2.58	.556	-.255
						Green sandy silt, also one pc. laminated white cherty shale 20 cm. long, and one pc. limestone 5 cm. long. Probably at outcrop[6] Abundant fauna, numerous brachiopods.			

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[6] Described in Emery and Shepard (1945).

TABLE II. . OFFSHORE BOTTOM SAMPLES IN VICINITY OF MUGU LAGOON (continued)

Sample File No.	SIO Date No.	General Location	Sampler	Depth of Sample in Feet5/	Depth in Core (cm)	Md	So	Sk	Log$_{10}$Sk
F125D	23 May 38 FPS 125	47 Fathom Ridge	Large Dredge	282 (47 fath.)		Shell, some mud, and one pc. of black chert, 6 cm. long; surface altered to grey. (miocene age?)			
F126D	23 May 38 FPS 126	47 Fathom Ridge	Large Dredge	282 (47 fath.)		14 large pcs. of crystalline limestone, angular grey, max. diameter 35 cm. Clearly washed no sand or mud (except in crack of one rock)6/			
F304C	29 Nov 38 FPS 304	Canyon West of Mugu Canyon (axis)	Emery-Dietz Corer	876 (146 fath.)	0-2.5	.015	3.56	.475	-.323
					25-10	.020	2.95	.466	-.332
					35-43	.020	2.80	.545	-.263
					84-92	.018	3.16	.482	-.317
					137-145	.019	3.03	.463	-.334
					175-183	.016	3.17	.658	-.182
						183 cm. core, 390 cm. penetration, 0-3 cm. mobile layer. Color of core blackish green.			
F305C	27 Nov 38 - FPS 305	Mugu Canyon (axis)	Emery Dietz	930 (155 fath.)		Core nose smashed; core barrel contained 6 pc. angular grey sandstone, high arkosic; chlorite and calcite cement. Max. diam. 5 cm. Probably center of outcrop in canyon.6/			

6/ Described in Emery and Shepard (1945).

TABLE III. FAUNA

Sample M2D. Shells (Fossil?) from material dredged between 5 and 15 feet below bottom of Mugu Lagoon, by hydraulic dredge, and picked up at pipe outlet. Depth approximately 10 feet below MLL water.

Genus and Specie		Geologic Distribution (from Grant & Gale, 1931)
Pecten circularis Sowerby	(Fossil?)	Pliocene to Modern
Saxidomus giganteus (Deshayes)	(Fossil?)	Pliocene to Modern; present distribution from Alaska to Monterey.
Venerupis staminea (Conrad)	(Fossil?)	Miocene to Modern
Macoma nasuta (Conrad)	(Fossil?)	Miocene to Modern
Tagelus californianus (Conrad)	(Fossil?)	Pliocene to Modern
Sinum debile (Gould)(?)	(Fossil?)	Pliocene to Modern

Listed in order of their abundance. Living specimens of all except *Saxidomus giganteus* and *Sinum debile* were collected by Dr. M. W. Johnson from Mugu in November of 1937. Living *Saxidomus giganteus* apparently do not extend as far south as Mugu Lagoon.

Sample M49D. Fauna dredged from 7 Fathom Ridge; depth, 102 to 40 feet.

Polinices draconis (Dall) (dead) covered with barnacles, *Balanus tintinnabulum californicus* Pilsbry (living), and housing a hermit crab (living).

Gastropod unidentified (living)

Crab unidentified (living)

Several starfish, *Pisaster*? (living)

Sample M50D. Fauna dredged from 7 Fathom Ridge; depth, 42 to 120 feet.

Polinices draconis (Dall) (dead), covered with barnacles, *Balanus tintinnabulum californicus* Pilsbry (living) and housing a hermit crab (living).

Cryptoconus carpenterianus (Gabb) (dead?), covered with several small barnacles, *Balanus tintinnabulum californicus* Pilsbry (living).

Crepidula sp. (living)

Venerupis (Callithaca) tenerrima Carpenter (living)

Several starfish, *Pisaster*? (living)

TABLE III. FAUNA (continued)

Genus and Specie		Geologic Distribution
Sample M57C. Core from East Canyon head, depth 275 feet. Depth in core, 21 cm. below surface.		
Bittium quadrifilatum Carpenter	(Fossil?)	Pliocene to Modern
Sample M62C. Core from Mugu Canyon axis, depth 480 feet. Depth in core, 25-27½ cm. below surface.		
Mitrella aurantiaca Day	(Fossil?)	
Dendraster sp.		
Balanus sp.		

TABLE IV. FORAMINIFERAL COUNT

BENTHIC FORMS	Sample No:	M47	M51D	M52	M69
	Depth in feet:	40	127-75	159	330
		%	%	%	%
Bolivina costata d'Orbigny		**			
Bolivina interjuncta Cushman		5	6	11	
Bolivina serrata Natland					**
Bolivina sp.				**	
Bolivina subadvena Cushman			**		
Bolivina subexcavata Cushman and Wickenden		**		**	
Bolivina vaughani Natland		**			**
Bulimina pagoda v. hebespinata Stewart and Stewart					**
"Bulimina pulchella d'Orbigny"			6		
Buliminella elegantissima d'Orbigny*		57	29	25	53
Buliminella sp.			**		
Buliminella subfusiformis Cushman				7	
"Cassidulina subglobosa H. B. Brady"			6		
Discorbis sp.		2		**	
Elphidium sp.		10			13
Elphidium spinatum Cushman and Valentine*		3	**		
Elphidium translucens Natland		4	16	14	
Eponides patagonica (d'Orbigny)			13		
Gyroidina sp.				**	
Labrospira columbiense Cushman		4	**		
Nodosaria scalaris Batsch					**
"Nonion scapha (Fichtel and Moll)"*		2	6	14	**
Nonionella miocenica v. stella, Cushman and Moyer		3	6		
Uvigerina sp.				14	
Quinqueloculina sp.		7			
Total Number Benthic Forms Counted		100	31	28	15
Total Number of Pelagic Forms Counted (Globigerina sps.)		28	15	12	16

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* Forms characterizing Natland's (1933) Temperature-Depth Zone II: 13.2-21.4°C and 14-125 feet.

**Single specimen only.

FIGURE 1

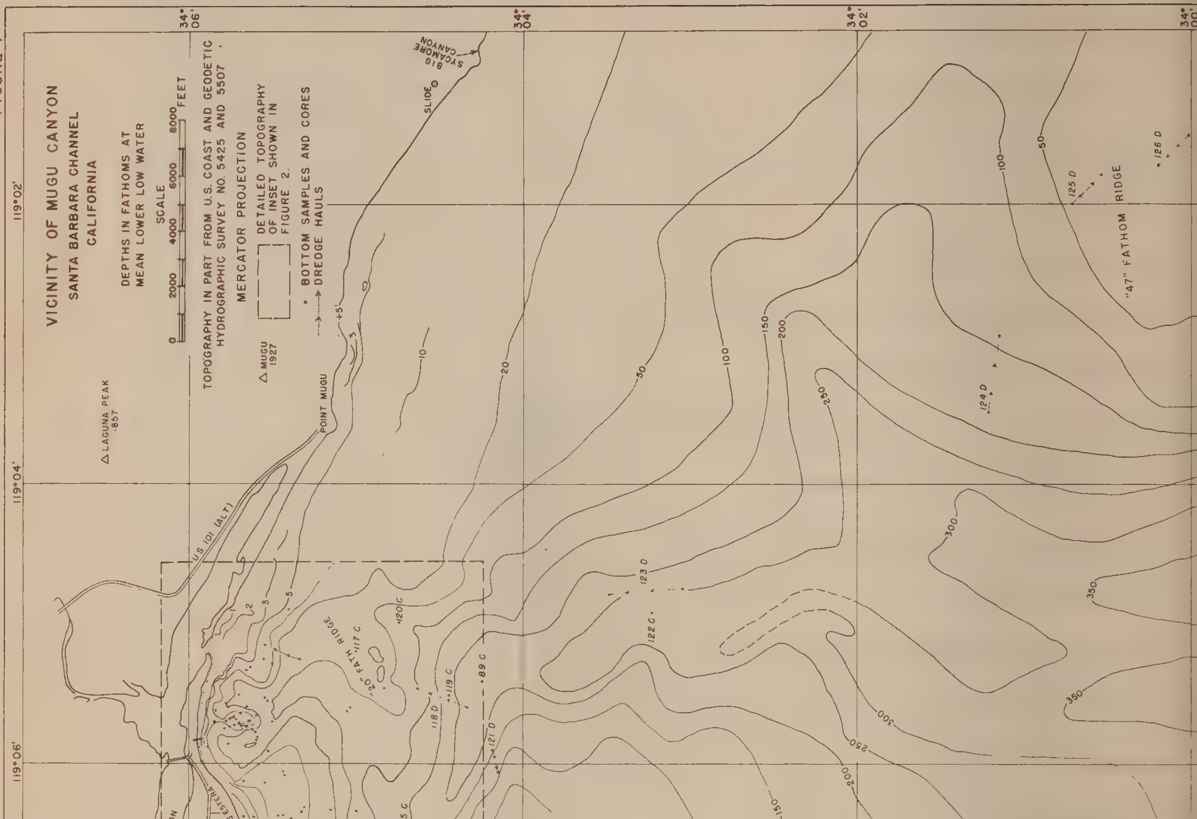
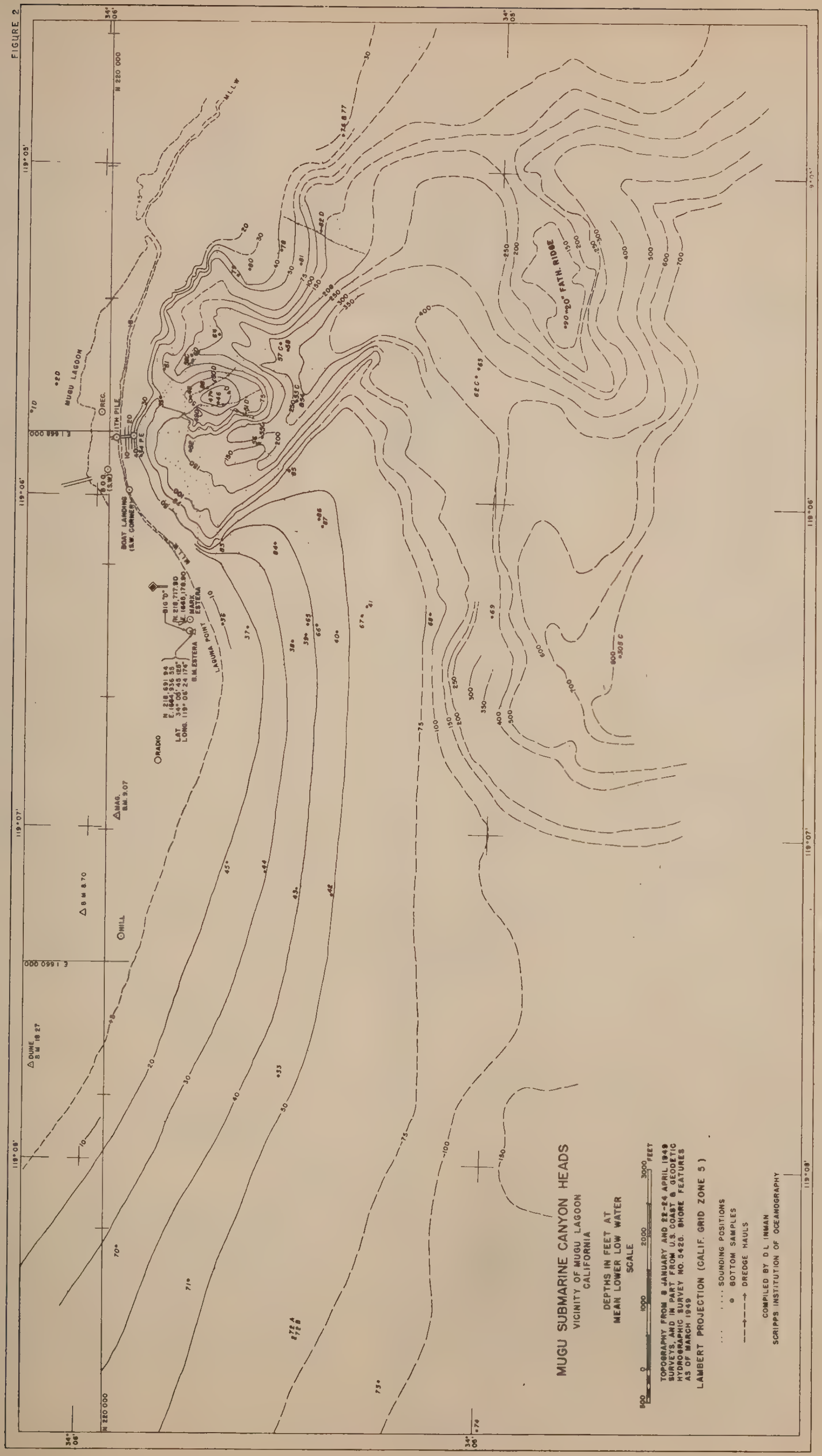

VICINITY OF MUGU CANYON
SANTA BARBARA CHANNEL
CALIFORNIA
DEPTHS IN FATHOMS AT MEAN LOWER LOW WATER
SCALE
0 2000 4000 6000 8000 FEET
TOPOGRAPHY IN PART FROM U.S. COAST AND GEODETIC HYDROGRAPHIC SURVEY NO. 5425 AND 5507
MERCATOR PROJECTION
DETAILED TOPOGRAPHY OF INSET SHOWN IN FIGURE 2.
• BOTTOM SAMPLES AND CORES
DREDGE HAULS
MUGU 1927
LAGUNA PEAK 1457
POINT MUGU
US 101 (ALT)
BIG SYCAMORE CANYON
SLIDE
MUGU LAGOON
LAGUNA POINT
RADIO
B.M. 9.07 MAG
ESTERO
DUNE B.M. 18.27
WEST B.M. 14.02
20 FATH. RIDGE
"47" FATHOM RIDGE
119°02'
119°04'
119°06'
119°08'
119°10'
34° 06'
34° 04'
34° 02'
34° 00'
SANTA YNEZ MTS.
SANTA BARBARA
VENTURA
SANTA CLARA R.
CALLEGUAS CREEK
OXNARD PLAIN
HUENEME
SANTA MONICA MTS.
LOS ANGELES
MUGU SUBMARINE CANYON
SANTA MONICA BASIN
SANTA CRUZ I.
50 FMS.
100 FMS.
450 FMS.
N

FIGURE 2



MUGU SUBMARINE CANYON HEADS
VICINITY OF MUGU LAGOON
CALIFORNIA

DEPTHS IN FEET AT
MEAN LOWER LOW WATER

SCALE

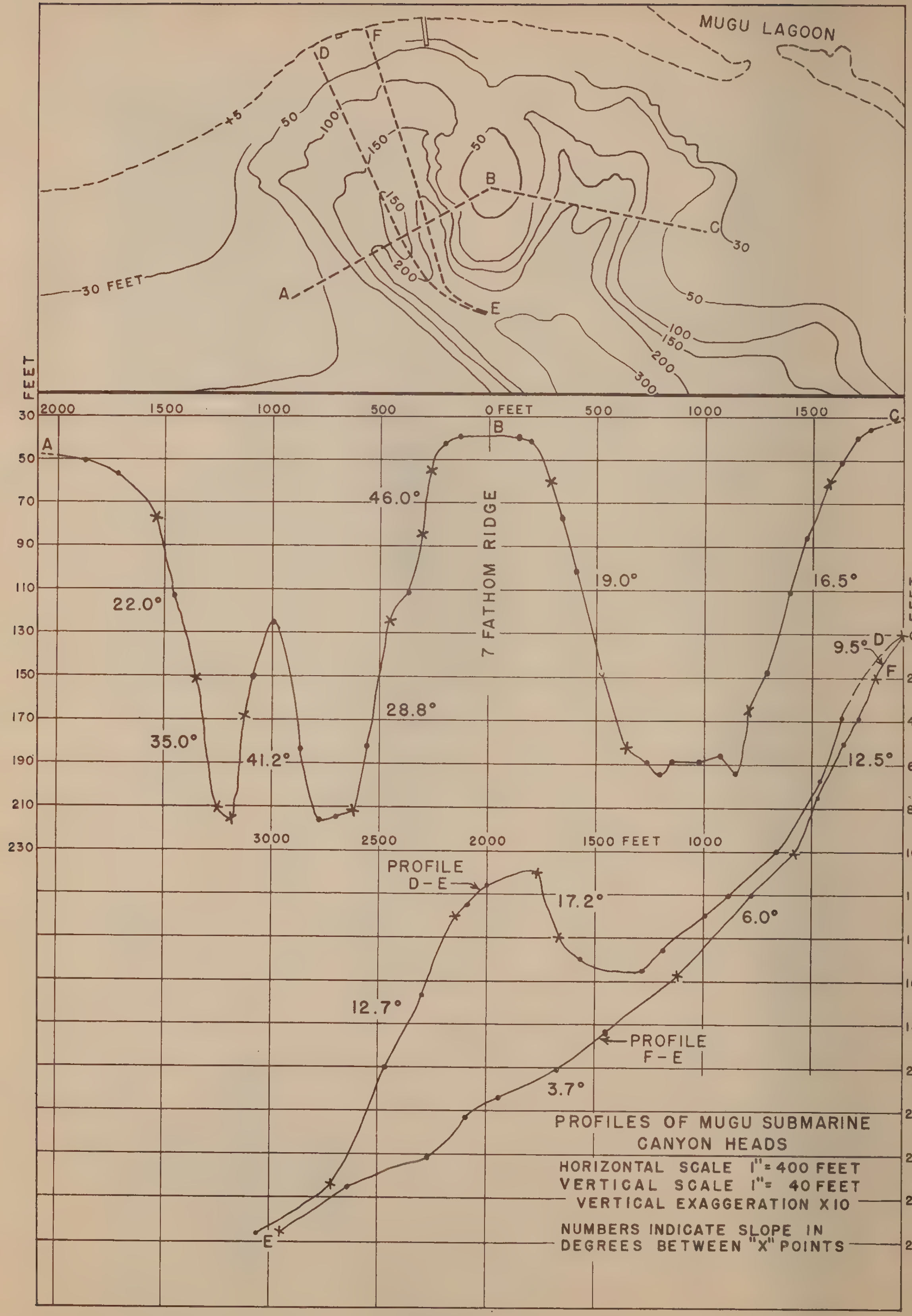
TOPOGRAPHY FROM 8 JANUARY AND 22-24 APRIL 1949 SURVEYS, AND IN PART FROM U.S. COAST & GEODETIC HYDROGRAPHIC SURVEY NO. 5426. SHORE FEATURES AS OF MARCH 1949

LAMBERT PROJECTION (CALIF. GRID ZONE 5)

COMPILED BY D L INMAN
SCRIPPS INSTITUTION OF OCEANOGRAPHY

500
0
1000
2000
3000
FEET
.... SOUNDING POSITIONS
● BOTTOM SAMPLES
—→— DREDGE HAULS
MUGU LAGOON
REC.
11TH PILE
BOAT LANDING (S.W. CORNER)
BIG "D"
N. 218,717.80
E. 1,666,170.90
MARK ESTERA
B.M. ESTERA
LAT. 34° 06' 45.125"
LONG. 119° 06' 24.176"
N. 218,691.94
E. 1,664,936.55
LAGUNA POINT
RADIO
MAG. B.M. 9.07
B M 8.70
HILL
DUNE B M 10.27
WEST (B.M 14.02)
MLLW
"20" FATH. RIDGE
N 220 000
E 1 666 000
E 1 660 000
119°05'
119°06'
119°07'
119°08'
34°05'
34°06'

FIGURE 3

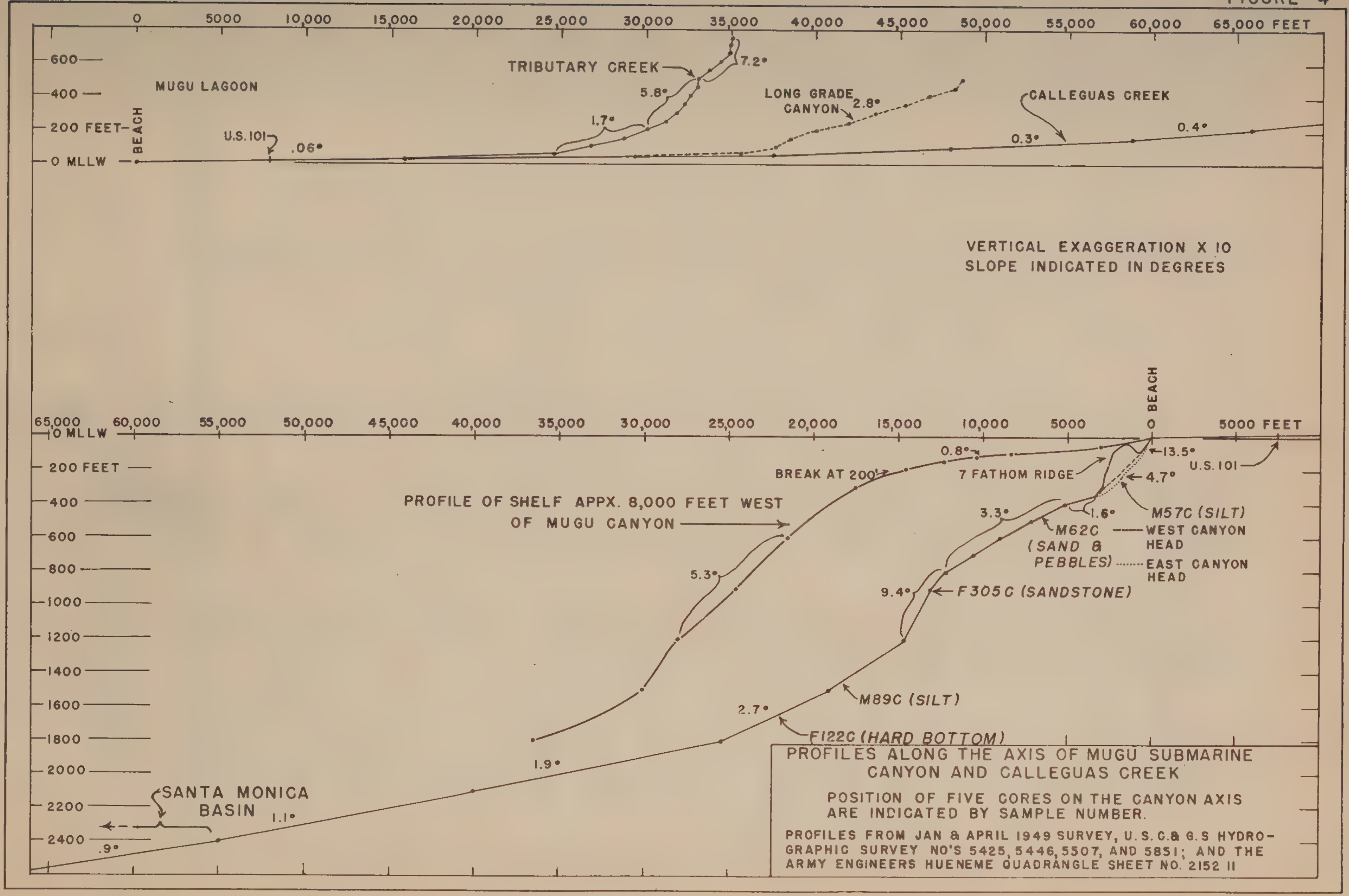


PROFILES OF MUGU SUBMARINE CANYON HEADS

HORIZONTAL SCALE 1" = 400 FEET
VERTICAL SCALE 1" = 40 FEET
VERTICAL EXAGGERATION X10

NUMBERS INDICATE SLOPE IN DEGREES BETWEEN "X" POINTS

FIGURE 4

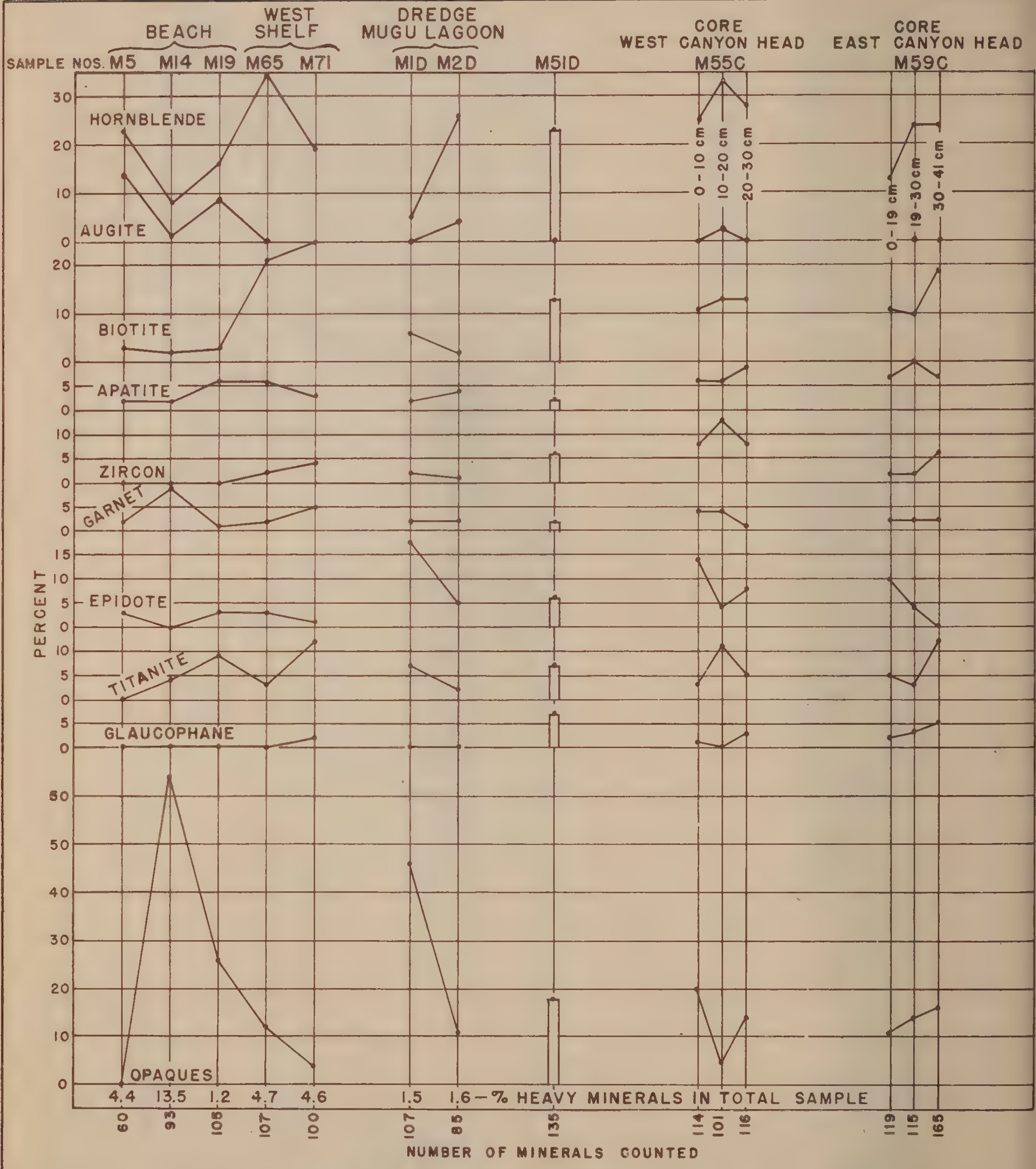


PROFILES ALONG THE AXIS OF MUGU SUBMARINE CANYON AND CALLEGUAS CREEK

POSITION OF FIVE CORES ON THE CANYON AXIS ARE INDICATED BY SAMPLE NUMBER.

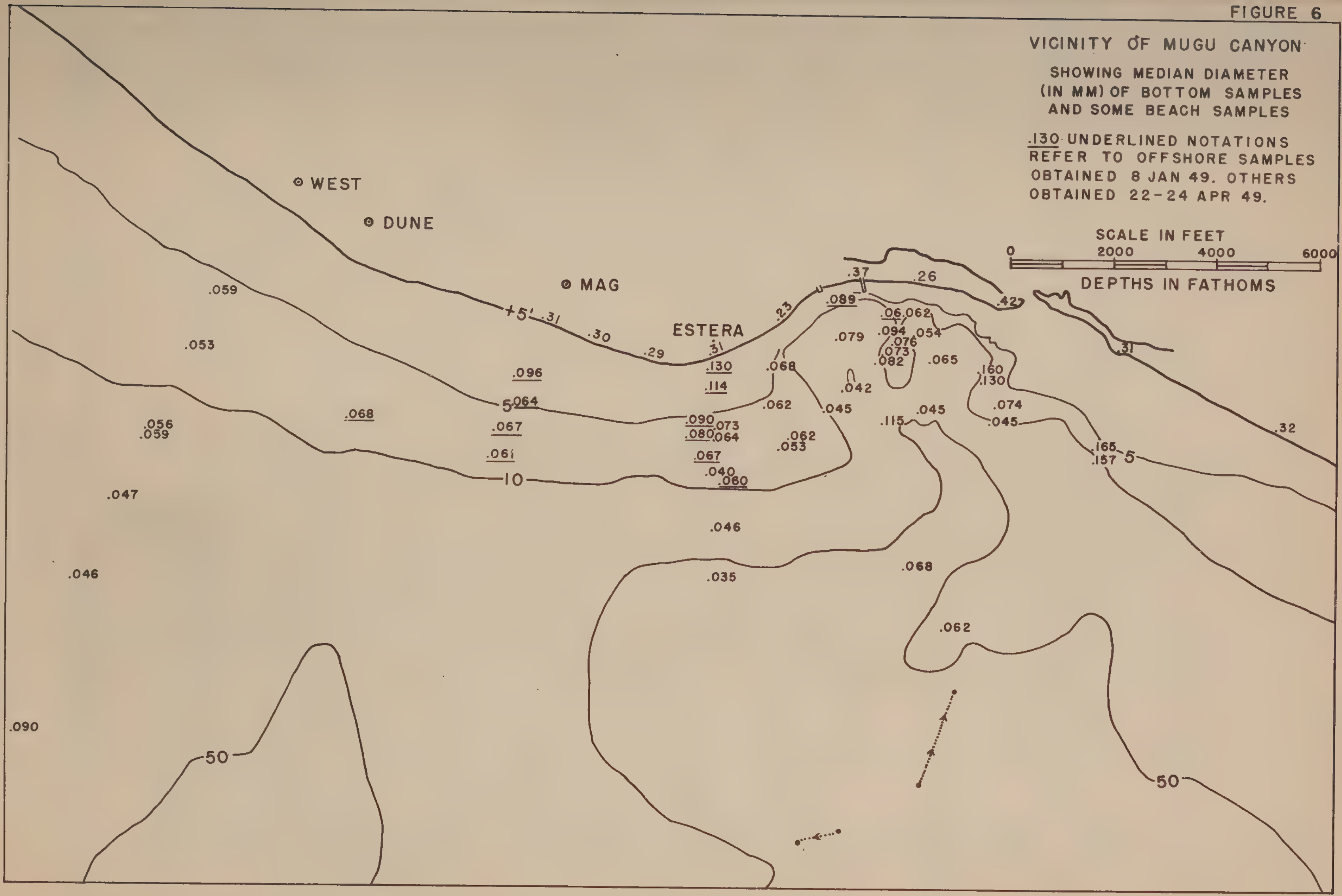
PROFILES FROM JAN & APRIL 1949 SURVEY, U. S. C.& G. S HYDROGRAPHIC SURVEY NO'S 5425, 5446, 5507, AND 5851; AND THE ARMY ENGINEERS HUENEME QUADRANGLE SHEET NO. 2152 II

FIGURE 5



VARIATION IN HEAVY MINERAL CONTENT OF MUGU SAMPLES

FIGURE 6



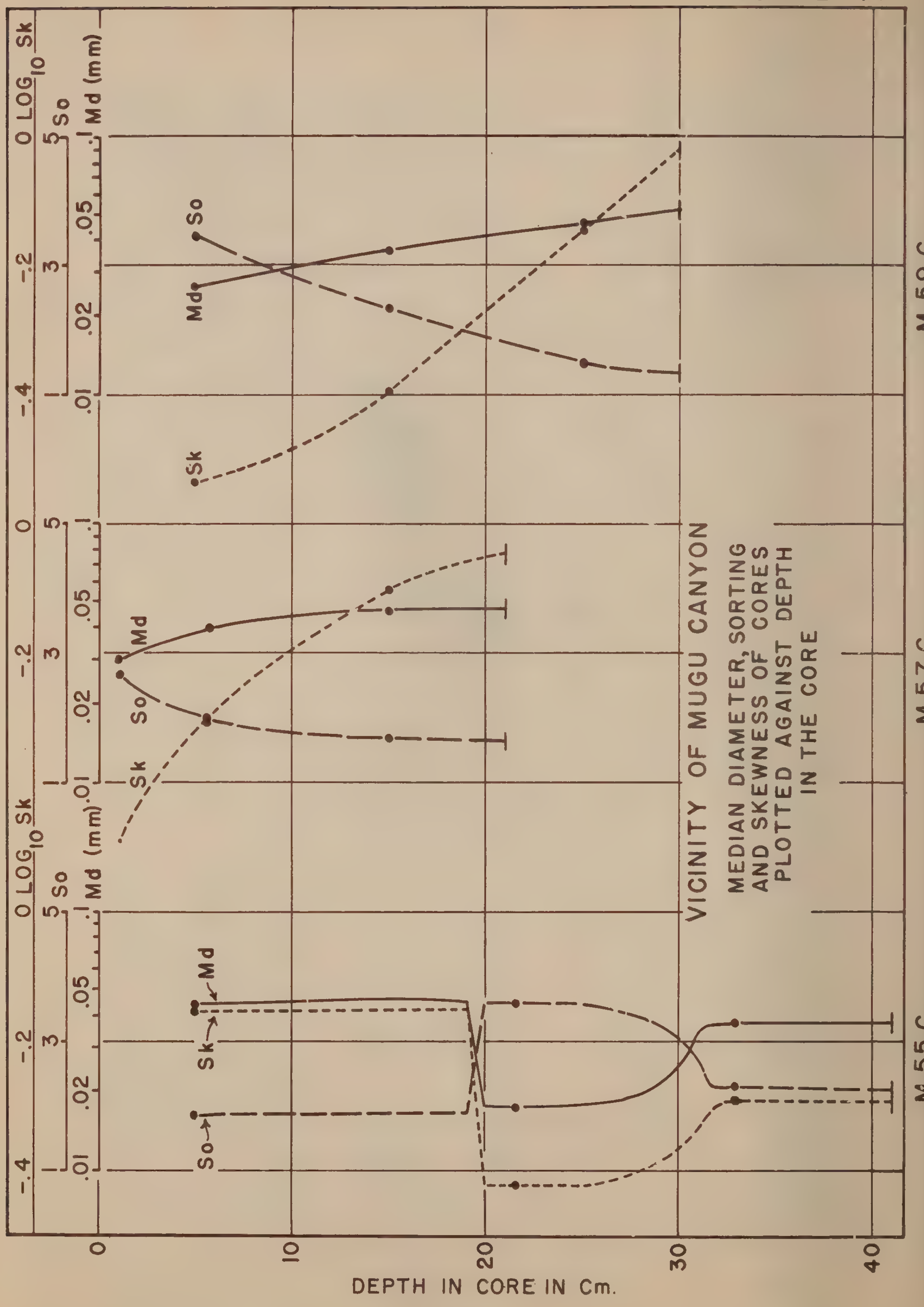
VICINITY OF MUGU CANYON

SHOWING MEDIAN DIAMETER (IN MM) OF BOTTOM SAMPLES AND SOME BEACH SAMPLES

.130 UNDERLINED NOTATIONS REFER TO OFFSHORE SAMPLES OBTAINED 8 JAN 49. OTHERS OBTAINED 22-24 APR 49.

SCALE IN FEET
0
2000
4000
6000
DEPTHS IN FATHOMS
WEST
DUNE
MAG
ESTERA
+5'
5
10
50
50
.059
.053
.056
.059
.047
.046
.090
.068
.096
.064
.067
.061
.31
.30
.29
.31
.23
.37
.26
.42
.31
.32
.130
.114
.090
.080
.073
.064
.067
.040
.060
.046
.035
.068
.062
.062
.053
.089
.079
.045
.042
.06
.062
.094
.054
.076
.073
.082
.065
.115
.045
.160
.130
.074
.045
.165
.157
.068
.062

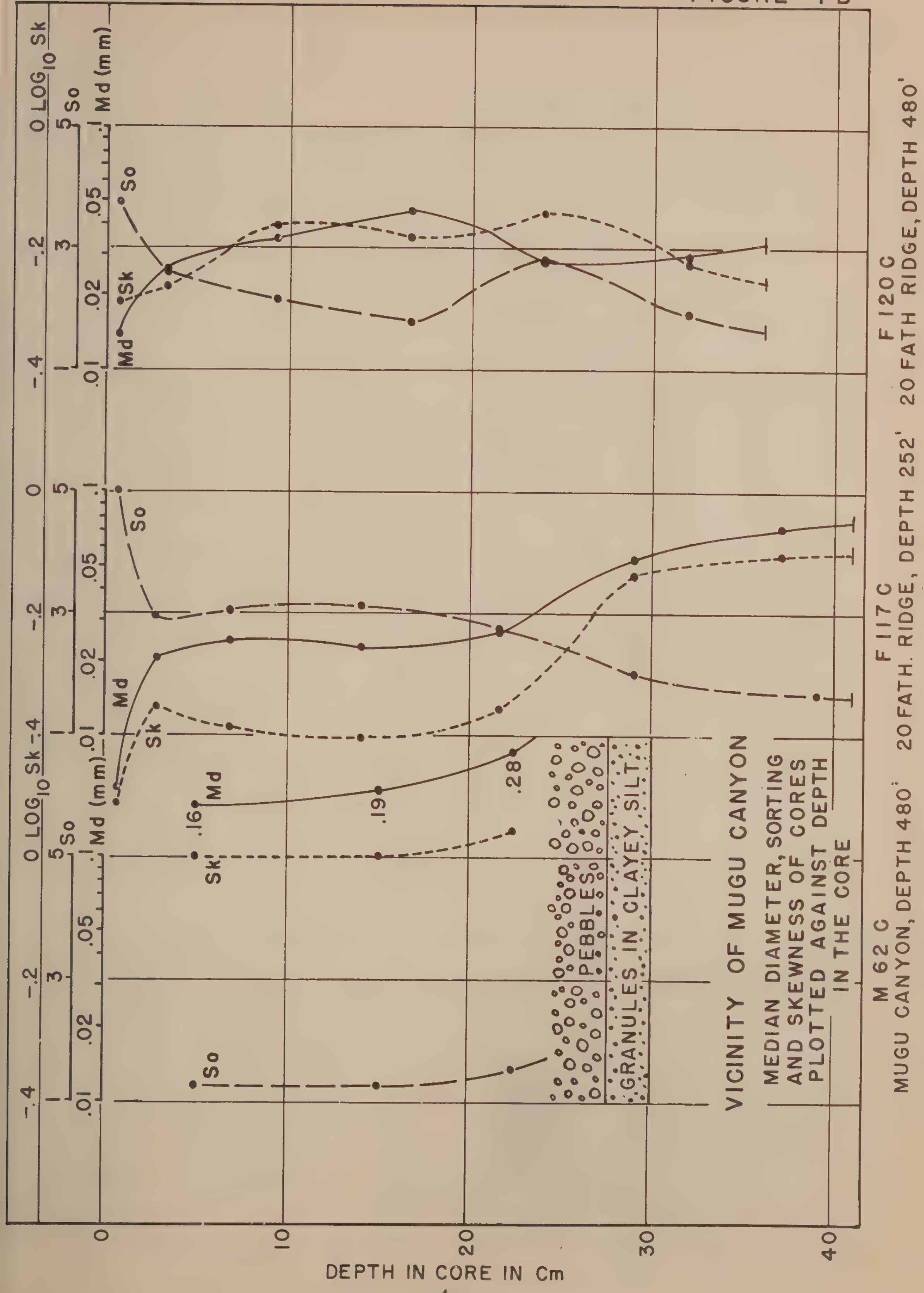
FIGURE 7A



VICINITY OF MUGU CANYON

MEDIAN DIAMETER, SORTING AND SKEWNESS OF CORES PLOTTED AGAINST DEPTH IN THE CORE

FIGURE 7B



VICINITY OF MUGU CANYON

MEDIAN DIAMETER, SORTING AND SKEWNESS OF CORES PLOTTED AGAINST DEPTH IN THE CORE

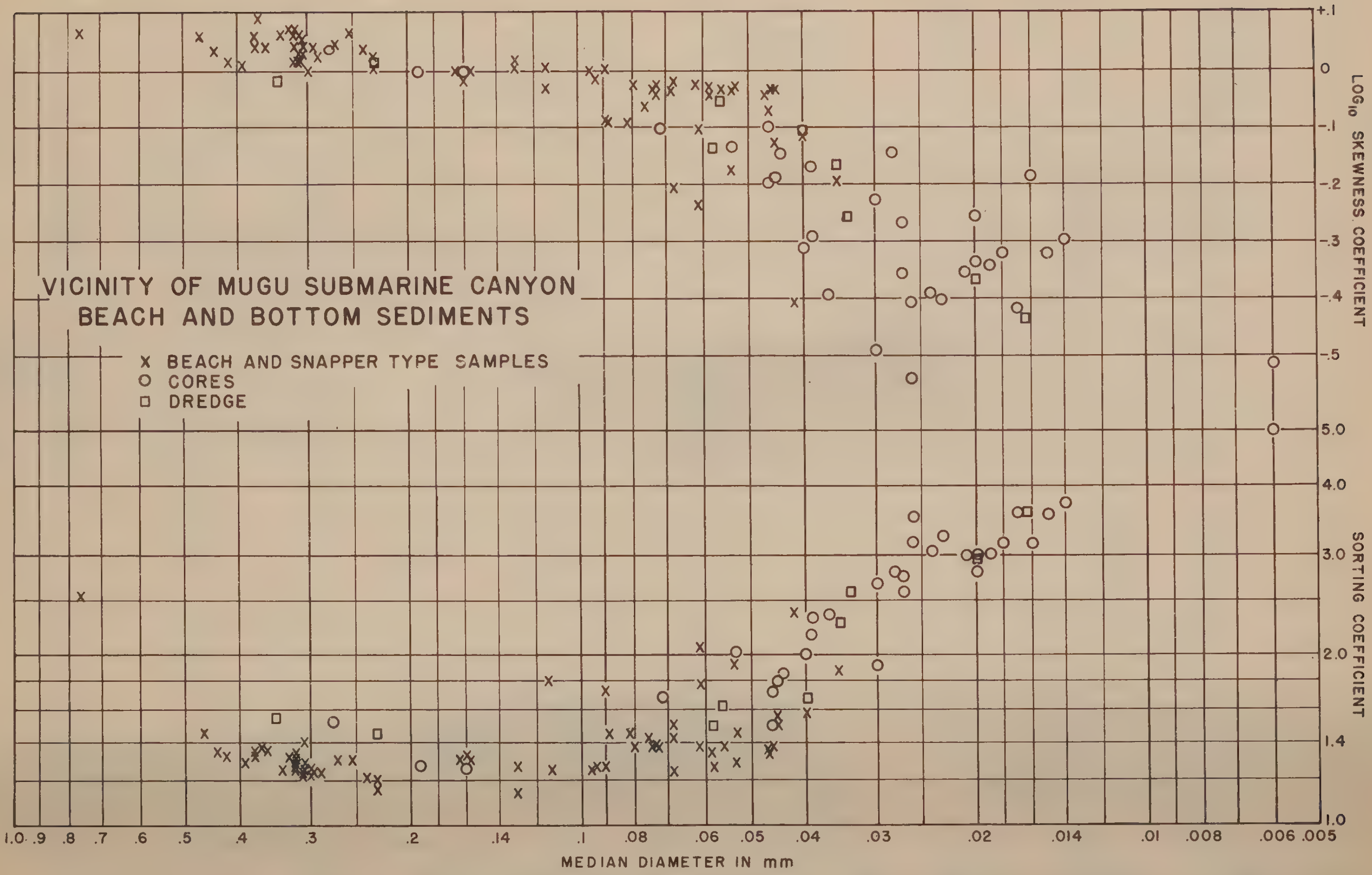
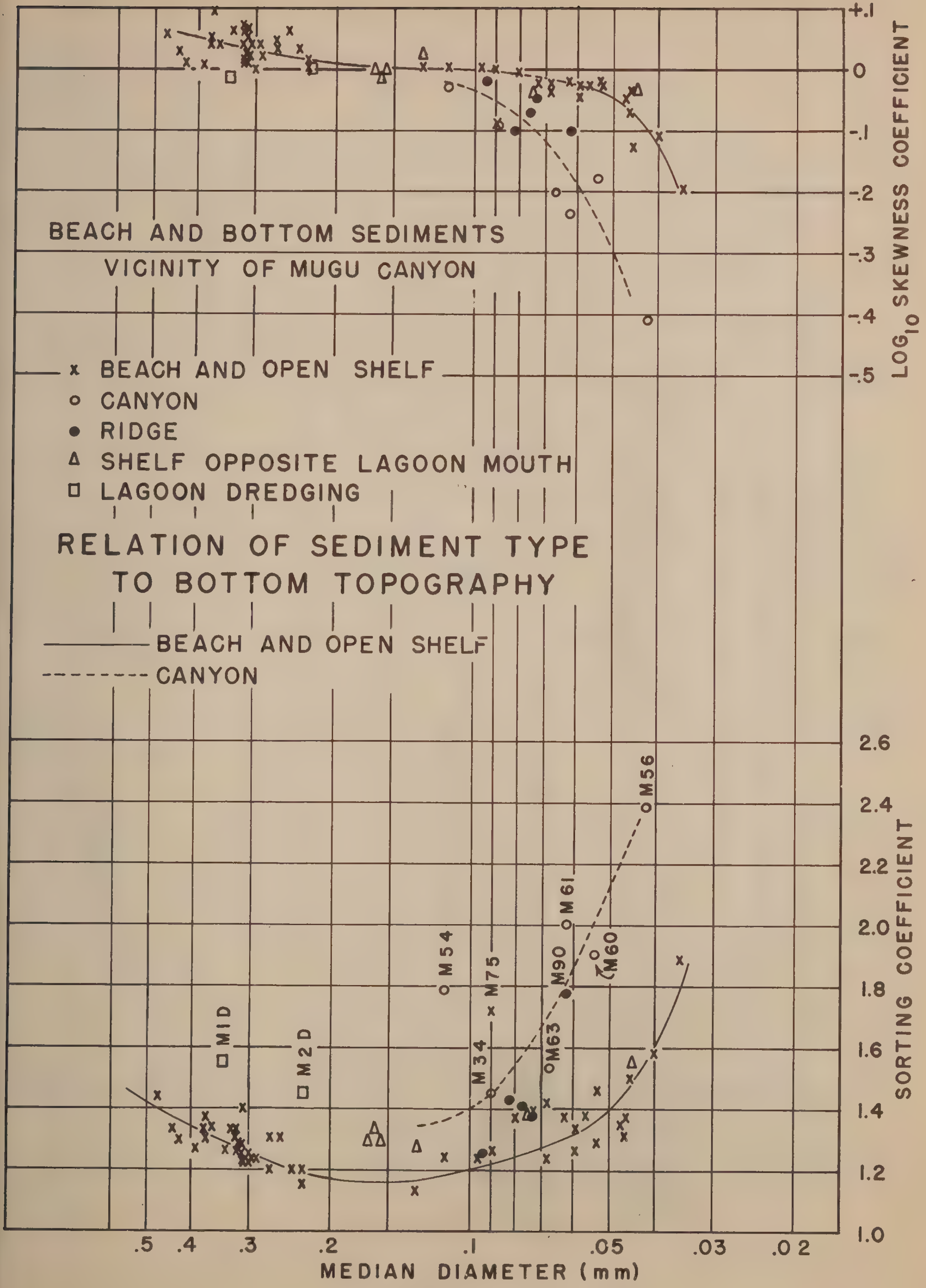


FIGURE 8. RELATION OF SORTING AND SKEWNESS TO MEDIAN DIAMETER FOR ALL SEDIMENT SAMPLES INCLUDING CORE SEGMENTS

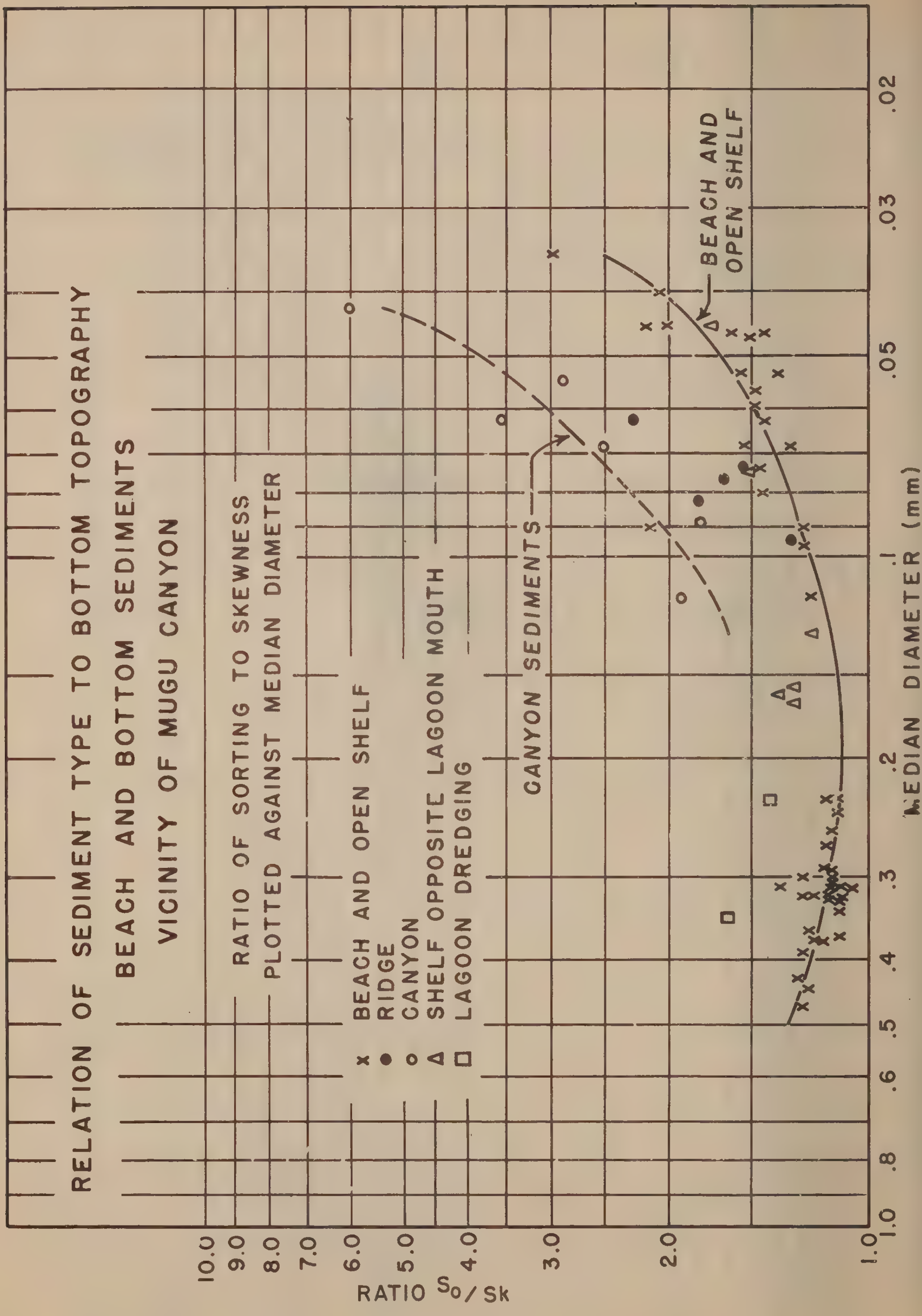
FIGURE 9A



BEACH AND BOTTOM SEDIMENTS
VICINITY OF MUGU CANYON

RELATION OF SEDIMENT TYPE
TO BOTTOM TOPOGRAPHY

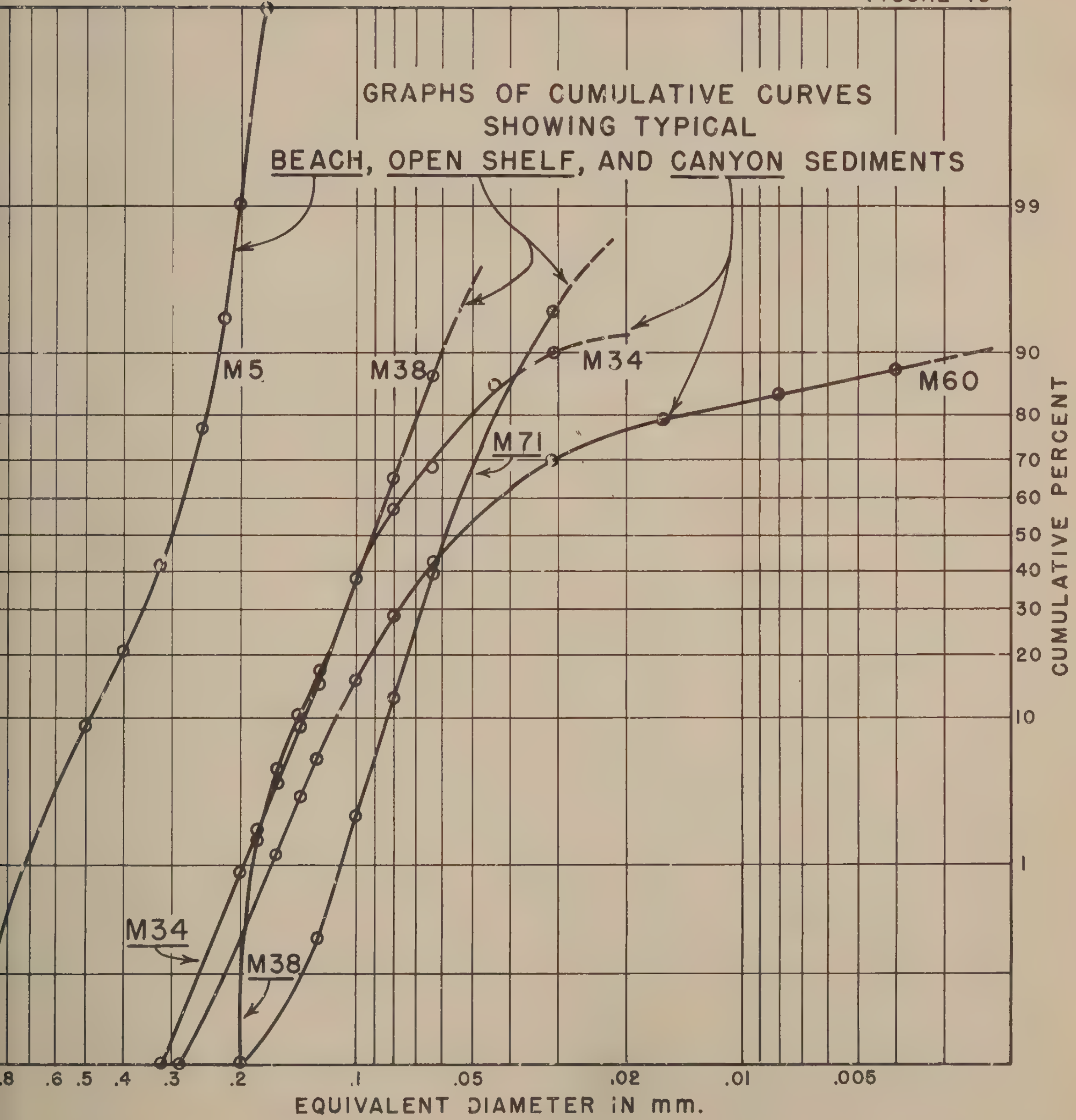
FIGURE 9B



RELATION OF SEDIMENT TYPE TO BOTTOM TOPOGRAPHY
BEACH AND BOTTOM SEDIMENTS
VICINITY OF MUGU CANYON

RATIO OF SORTING TO SKEWNESS
PLOTTED AGAINST MEDIAN DIAMETER

FIGURE 10



GRAPHS OF CUMULATIVE CURVES
SHOWING TYPICAL
BEACH, OPEN SHELF, AND CANYON SEDIMENTS

Contribution No. 474

BEACH CYCLES
IN SOUTHERN CALIFORNIA

TECHNICAL MEMORANDUM NO. 20
BEACH EROSION BOARD
CORPS OF ENGINEERS

JULY , 1950

Contribution from the Scripps Institution of Oceanography, New Series, No. 474

FOREWORD

This paper was prepared by Francis P. Shepard of the University of California. The report appeared in limited issue as Submarine Geology Report No. 11 of the Scripps Institute of Oceanography, Scripps Contribution No. 474, University of California. It is believed that the results of the investigations outlined herein are of sufficient value to merit publication at this time.

The opinions and conclusions expressed by the authors are not necessarily those of the Board.

The authority for publication of this report was granted by an act for the improvement and protection of beaches along the shores of the United States, Public Law No. 166, 79th Congress, approved July 31, 1945.

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BEACH CYCLES IN SOUTHERN CALIFORNIA

ABSTRACT

The large waves accompanying winter storms cause a widespread denudation of southern California beaches. During the summer period of small waves the sand is brought back, completing an annual cycle. The beach berms vary in width with the seasonal changes so that in general they are widest at the end of summer and narrowest at the end of winter. Variation in berm width is related also to the spring and neap tides, the berms being widest during neap tides and narrowest during spring tides. The cutting back of the berms often results in scarp formation at the top of the foreshore, the scarps being most commonly developed in the fall during the first period of large waves following the small waves of summer. In addition to offshore-onshore movements of sand there are also important lateral shifts. The sand is shifted along the beach in the direction in which the waves are approaching. As a result of this lateral shift the northwest storms of winter cause the southern ends of some beaches to grow during the winter, and the southerly approach during the summer moves the sand north and therefore produces a cut.

Some partially protected beaches lack seasonal changes. Certain beaches have undergone long period changes which are non-cyclincal; some of these changes are associated with engineering structures. All beaches must have a permanent loss of sand during the period of maximum cut. This loss from pocket beaches enclosed between headlands is believed to be very small since many of them have very meager sources of new sand. The more extensive open beaches, however, have a large loss of sand because of a net seasonal migration along the shore in the direction of dominant wave approach or because of sand settling into submarine canyons. In general this loss is replenished by new sources of sand introduced by floods and cliff erosion.

Introduction

The California state law gives beach rights to owners of coastal property as far as the mean high tide line.[1] Actually, this line, as applied to beaches on the exposed California coast, is constantly shifting, being affected by virtually every high tide during both large and small wave conditions. During the course of a year the mean high tide lines on many beaches shift hundreds of feet seaward and landward.

Several years before World War II investigations of the changes in southern California beaches were begun by U. S. Grant IV, E. C. LaFond

[1] Some old land grants extend rights farther seaward.

and the writer. A mass of records had been accumulated by the time that the war interfered with the studies. Late in the course of the war the need for information concerning beach landing operations led to the resumption of the studies under Navy grants to the University of California, both at the Berkeley campus and at Scripps Institution. This work has continued to date under Army and Navy **sponsorship.** As is so often the case, the extension of the beach studies has led to the finding that the simple solutions, which were suggested at first, are not satisfactory. Many of the problems are still unsolved but the data have accumulated to such an extent that some of the salient features which have been observed to date are discussed here and an attempt is made to interpret some of the results.

Acknowledgments

In addition to the help received from Army and Navy appropriations, the writer has been assisted in this work by a large number of individuals. Appreciation is expressed particularly to Messrs. D. L. Inman, E. C. LaFond, and D. B. Sayner and Miss Ruth Yound. Dr. Roger Revelle made helpful suggestions in the revision of the manuscript.

Definitions

The present discussion restricts the term "beach" to sediment-covered areas along the shore which are exposed by the lowest tides and covered by the highest tides and largest waves. Figure 1 illustrates various beach terms used in the present article. This diagram is taken with slight changes from Shepard (1948a, fig. 33) and is also very similar to that which appeared in the Interim Report of the Beach Erosion Board of the U. S. Engineers (1933). The diagram indicates the common features of beaches, coast and offshore, although most beaches lack some of these features at least part of the time. Thus many beaches have no berms and others lack low tide terraces. The berm crest of earlier diagrams is changed in the present treatment to berm edge because crest suggests a high point whereas the outer berm margin may be the lowest part of the berm, especially on fine sand beaches. Seaward of the berm edge the shore slope may be even or a beach scrap may exist (figure 2). The latter may be vertical if recently cut, but the scarp is soon reduced to an angle of repose as shown in the upper scarp of Figure 2 where an old scarp has been partially covered by the building of a new berm. Subsequent erosion has formed a new scarp, cutting away a portion of the double berm. The beach may be horizontal inside the berm edge, it may slope shoreward, or it may slope seaward.

Changes Associated with Breaker Height

Seasonal Changes in Beach Profiles.

In southern California the large waves reaching shore come mostly from the stormy area lying 100 to several thousand miles off the coast. On some occasions these waves are augmented by local windstorms which rarely exceed 30 miles an hour. The storms which produce most of the high waves occur during the winter and spring, although occasional periods of large waves are observed during the summer. Most of the high summer waves come from gales in high latitudes in the southern hemisphere, but a few are derived from the hurricanes off and along the Mexican coast.

Since most of the large waves occur in winter and spring, it is not surprising that the beaches are most denuded of sand during those seasons. A comparison of profiles taken along the same range at a series of southern California and central California beaches,[2] (figures 4, 5, and 6) shows striking seasonal differences. Almost all of the beaches in southern California are cut back in winter and spring. The berm virtually disappears from many of the beaches. In some cases the sand cut from the outer berm is piled up and forms a high bern on the inside above the previous berm (see the Pt. Reyes section, figure 5). However, the great bulk of the sand cut from the berm is carried seaward. In some cases fill takes place on the lower portion of the foreshore (see figure 5) but more commonly the sand is carried well beyond the low tide line.

The sections along Scripps Beach (figure 6) show that winter cut takes place along this entire beach. However, the cut is small along sections F to H, and is large in sections C and D. The difference is the result of wave refraction due to the La Jolla Submarine Canyon (Munk and Traylor, 1947). Because of divergence the waves are much lower along sections F to H, which lie on the inside of the canyon (see figure 9), whereas the waves reach a maximum at C and D which represent the zone of convergence north of the canyon. Similarly the cut is very small on the south side of Pt. Sur (figure 5) where the beach is protected from the violent northwesterly storms and very large on the north side where these storms hit with great fury. The southern ends of several beaches build seaward in winter and cut back in summer. These special cases will be considered later.

Berm Variations. Most southern California beaches have berms at least during the season of greatest growth. The berm width is a good index of beach variation throughout the year and the necessary data are more easily obtained than are profile measurements. The variation with season at a series of beaches in southern California is indicated in Figure 7.[3] Many of these graphs do not run through the entire year but they all show the change from winter to summer so that the rest of the cycle can be inferred. It will be observed that the majority of these graphys show summer fill and winter cut, being in agreement with the profiles of Figures 4 to 6. The exception at San Onofre at the south end of the Cove (Fence Station, section G) is particuarly impressive since it has been observed for 5 years and is therefore almost as well established as are the normal changes at the La Jolla beaches. The reverse from normal winter cutting in the vicinity of the mouth of Mission Bay (sections T and U) is probably an unusual occurrence. Fragmentary records of this area taken in other years show summer fill and winter cut. Balboa Pier (section B) and North San Clemente (section E) may have winter fill and summer cut although the evidence is not very conclusive. The beach at Balboa Pier faces south-southwest and is largely protected from the winter storms, whereas it is exposed to the long southerly swell of summer. This may explain the apparent reversal.

2/ See Figure 3 for all beach locations, except those in the La Jolla area which are shown in Figure 9. Shepard (1948b) includes more detailed maps of most of the areas.

3/ Note that the base line for these graphs represents an arbitrary range.

A daily study of the berms along the beach south of Scripps Institution showed some of the factors causing this berm variation. Two major factors are illustrated by Figure 8. The berms are cut back as the result either of large waves or of the high water levels of spring tides. Both of these influences can be detected from the variations of the berm at Scripps Beach. The highest waves indicated on the diagram, June 12th, were quite free from berm cutting because this happened to be a time of very low tides so that the large waves were unable to attack the berm. The effect of the waves on the berm is not as well illustrated as is that of the tide during the period covered by Figure 8, although the slow berm growth in late September during a period of gradual increase in the height of the higher high tide but of small waves is unmistakable evidence. The cuts indicated on about the 19th of October during a period of decreasing tide heights is also a wave effect. In some instances, not shown on the diagram, the berms at Scripps Beach have been cut back 50 feet or more during the first period of large waves following the small waves of the summer. Such large cuts, however, have almost invariably occurred during spring tides.

The variations in the berm width will be seen to be larger at the two stations on Scripps Beach where the waves are higher as a result of convergence north of a submarine canyon than at the station taken at the head of the canyon where the waves are much smaller.

The cutting back of the berm during spring tides and times of high surf takes place as a result of the surge of the waves over the berm edge. Ordinarily the water returns along concentrated channels causing the straight berm edge to become crenulated. After a moderate retreat the ridges between bights are attacked by the convergence of the incoming surge so that the berm edge is again straightened.

It is possible that berms grow seaward by the direct addition of sand at the outer edge, but daily observations of berm growth at La Jolla indicate that the building out of the berms takes place by the development of double berms below the edge of the main berm. If low waves prevail, these double berms start developing during neap tides and are pushed landward during the succeeding spring tides. If the beach is undergoing a period of growth, the new berms are added to the old ones, often with little break in slope between the new and the old. Therefore, during these building periods each semi-lunar tidal cycle may show a new increment added to the old berm.

Scarp Formation in Retreating Berms. It has been observed that the beach berms may retreat with an even slope or the retreat may be accompanied by scarp formation below the berm edge, (figure 2). The scarps are much more common on steep coarse sand beaches where they not infrequently become 5 or 6 feet high. They occur less frequently on fine sand beaches, and, so far as has been observed, never with more than one or two foot elevations. The scarps develop during periods of large waves, particularly if the berms had been built out previously to their greatest extent, as for example at the time of the first large waves following the summer and fall period of berm growth.

There is some evidence that scarp development comes more at times of neap tides than at spring tides.

During local storms where short period waves cause heavy surging over the edge of the berm, scarps are less frequently developed. Thus profile measurements on Cape Cod just before and just after a relatively weak hurricane which it the coast in 1945 indicated a straightening of the slope (Shepard, 1949a, figure 19). Despite the violence of the storm and the great retreat of the berms, no scarps were discovered.

So far as can be told from available information, scarp formation is the result of concentrated surf action on the slope below the berm edge. Apparently the scarps develop on steep beaches better than on gentle, because the waves break nearer the berm edge and therefore violent cutting is more likely. The backwash down from the berm edge is necessarily more violent on a steep beach than on a gentle beach. The foreshores are always steepest after the berms have been extended seaward so that this state favors scarp formation. During neap tides the waves tend to develop the most concerted position of attack and thus to produce scarps.

Beach Changes Related to Wave Approach

Shifting of Pocket Beaches. Years of measurements of La Jolla beaches have shown numerous examples of cut at one place and contemporaneous fill at another. The shifts which take place in the small pocket beaches along the rocky coast which extends south from La Jolla are particularly impresive (figure 9). Boomer Beach, near La Jolla Cove, shows the most rapid transformations of this type (figure 10). On occasions during the course of 24 hours a 5 to 10 foot thickness of sand has virtually disappeared from one end of the beach, while at the same time the exposed rocks at the other end have become buried in sand to depths ranging up to about 8 feet. In general these changes take place more gradually as shown by measurements at 4 points evenly spaced along the beach (figure 11).

The shifting of sand along Boomer Beach is very definitely related to the direction of approach of the waves. This was clearly indicated by a period of southerly approaching swells in September 1949 which gradually modified the beach, cutting away the south end and building up the north. Later northwesterly approaching waves were accompanied by a beach change in the opposite direction. Since the beach faces northwest, the southerly swell, after refraction, approaches the beach from the south side and thus induces longshore currents to the north, accounting for the sand shift in that direction. Since the northwest waves approach essentially normal to the beach, the reason for the shift of sand to the south is not as obvious. However, these waves from the northwest carry water over the reef lying outside the north end of the beach and this water can escape only to the southwest along the shore, producing southerly currents. The longshore currents under the two directions of approach produce rip currents as follows: (1) near the north end of the beach but south of the reef with southerly waves, and (2) near the south end of the beach with northwesterly approach. The longshore currents transport sediment towards these outmoving rip and small counter currents carry a portion of the sediment landward inside the rips causing a local building of the beaches. This explanation is probably far from complete but must suffice while awaiting more information from concurrent studies of bottom water and sand movements using current meters and sediment traps.

Casual observations of shifts of this type might lead one to the belief that the waves simply carry sand along the beaches from one point to another, as suggested by Leypoldt (1941), rather than move it seaward and shoreward. Such an idea, however, loses its force when the effect of any unusually large waves is observed (figure 11). At such times the beaches are cut back by wave attack at all points where sand exists at the initiation of the waves.

In the pocket beach known as Windansea (see figure 9) there is the same shift from north to south in winter. The magnitude and clerity of these changes at Windansea is indicated by profiles made at two-week intervals (figure 12). The appearance of these pocket beaches is changed so completely that one unfamiliar with the local setting might think that they represented different localities.

The changes at Windansea Beach differ slightly from those at Boomer Beach because there is a submerged ridge off the center of the beach which causes wave convergence and piling up of water along the shore directly inside, similar to that described elsewhere for the convergence at Scripps Beach (Shepard and Inman 1950). When the waves approach from the northwest along the north-south trending beach at Windansea, the water from the convergence moves dominantly south and the principal rip current extends seaward near the south end of the beach. This in turn is accompanied by an eddy which builds up the sand at this end of the beach. The southerly approach reverses the direction and position of these currents, as would be expected.

Shifting of Beach Near a Submarine Canyon. The long, relatively straight beach which extends for a mile south of Scripps Institution (figure 9) is under the special influence of waves refracted by La Jolla Submarine Canyon. In general the maximum erosion occurs at the wave convergence north of the canyon. Water is moved shoreward in this zone of convergence and the resulting rise in sea level develops longshore currents flowing out from the convergence in both directions (Shepard and Inman, 1950, figure 3). As a result the material stirred up by the waves is moved in either direction. Munk and Traylor (1947, figures 8-12) have shown how the zone of wave convergence migrates according to the direction of approach and the period of the waves. The seasonal variation in the direction of wave approach changes the position of beach cutting.

A portion of the material cut away at the point of convergence tends to be deposited at a position which lies midway between the large rip which turns seaward from a feeder current derived from the convergence and a small rip which moves out from the divergence (see Shepard and Inman, 1950, figure 3). In this zone there are weak counter currents which carry material in to the beach. The zone is marked by a point of sand which is occasionally covered by great masses of kelp and eel grass. This zone of weak counter currents also shifts to some extent with the seasonal variation of wave approach.

In southern California a change in direction of wave approach usually occurs in the fall. During the summer most of the large waves have been coming from the southern hemisphere. Westerly and northwesterly approach set in during occasional storms in the fall and are repeated at infrequent intervals during the winter and spring. In spring the approach again becomes more southerly. The result is that in general the convergence is farther to the south during the fall and winter than in the spring and summer. Similarly the inter-rip zone of deposition is also shifted in the same direction. These effects have been shown during many years of measurement of sand height along the sea walls. Changes over a period of 7 years are indicated in Figure 12 where station D represents the convergence during the winter and station B the convergence zone during the spring.

Actually the effect of large breakers is to produce cut all along the Scripps Beach, as was shown to be the case at Boomer Beach. However, the cutting is greater at the convergences and smaller at the inter-rip zones and at the divergences.

Unusual Changes at San Onofre. The cove at San Onofre (Shepard, 1948b, figure 11), 50 miles north of San Diego, was one of the places chosen for beach profiles started in 1945. At the end of the period of measurements one station at the south end of this cove had proven to have a reversal of the usual winter cut and summer fill. As a result observations have been continued at infrequent intervals up to the present time. During the four and a half years of berm width observation, the same cycle has been repeated annually (figure 7, section G). Superimposed on the cycle is a net retreat of the coast in this area, the bank being cut back a little each summer.

The situation is somewhat similar to that at the south end of Boomer Beach where the same reversal takes place. The San Onofre locality, called "Fence" (because of a barbed wire fence remnant), lies at the south end of the cove. Outside this part of the beach there is a broad boulder-strewn terrace which is laid bare in part during the lowest tides. This terrace is more pronounced to the south where it produces conditions for good surf board riding at high or immediate stages of the tide. To the north, however, there is deeper water adjacent to the beach although similar boulders are exposed in a fringe below the sand at low tide.

It was supposed at first that the winter berm building at this unusual station must be balanced by a cut at the north end of the beach and the summer cut at "Fence" station by a fill to the north. However, this has not proven to be the case. A station called "Crescent" in the center of the cove and a station called "North San Onofre" at the north end have been observed for the past three years. These stations have shown very little change and northing which could be called seasonal. It was thought also that there might be a reversal in longshore currents with the coming of winter. Measurements of the longshore currents made at 10 day intervals for a year, however, failed to show any appreciable difference (Shepard, 1948b, p. 33). However, the change must be related in some way to the change in direction of wave approach during the seasons.

Beaches Lacking Cyclical Changes

The berm variation diagram (figure 7) shows a number of cases where beaches appear to have undergone little if any seasonal variation. La Jolla Cove (figure 9) a locality not included in the diagram because measurements are not available, has been observed on many occasions over the past 15 years. The narrow beach at this cove varies only slightly in width during the year and, unlike Boomer Beach which it adjoins, is not cut down to underlying rocks. When large waves are approaching from the right direction (west-northwest, long-period being the best), waves sweep high up onto the beach, sometimes reaching the cliffs at high tide. On such occasions the beach is steepened and occasionally small scarps are cut. When the waves have subsided, the beach grows back very rapidly to normal. The removal of the entire beach would constitute no greater cut than takes place during one storm at Boomer Beach. However, the situation differs radically from Boomer Beach in one respect. A reef on the outside, which is exposed at low tides, prevents the waves from breaking directly on the Cove beach.

Less certain evidence suggests that Shell Beach (figure 9), south of Boomer Beach, is not greatly affected by winter storms. This beach like the Cove beach, is protected by off-lying reefs. Similarly Casa Beach, which is protected by the small sea wall at the Casa de Manana Hotel and is therefore not attacked by large waves, shows little seasonal variation. Casa Beach did not exist until the sea wall was built. The wall was constructed to form a semi-protected pool for swimming, but, because it has stopped the summer sand movement to the north, the pool has gradually filled in. Sluices which allowed water access from the ocean to the south proved to be too small to prevent southward migrating sand from blocking this circulation so that a natural trap developed which held sand carried in from the northwest. The beach now nearly fills the pool. On rare occasions cutting on the south side of the wall exposes the sluices (figure 14) and allows a small portion of the sand to escape, but this has never cleared out the sand fill nor appreciably influenced its size.

Long-period Changes

In addition to seasonal changes or storm cutting, long-period variations occur on some of the beaches. One of the most puzzling of these is the apparent growth of the beach south of Scripps Institution. Part of the evidence for the growth comes from accounts of old residents who claim that in winter it was not unusual to find cobbles all along the beach. Confirmation of the denuded state of the beach comes from old photographs (see Shepard and Grant, 1947, pl. 3, figure 1) although the evidence is not as complete as one would like. The cobbles were exposed during the winters and springs of 1937[4] to 1946, but never to the extent described by the older residents. Since that time the exposures of cobbles have become very restricted in area and of very short duration. In the past two years (winter and spring 1948 to 1950) only scattered cobbles have been seen. Furthermore, the beach profiles show a great cutting even at the points of wave convergence

[4] When my observations began.

The cause of the failure of the beach to cut deeply during the storm season in recent years is not readily apparent. The waves in recent years appear to have been of comparable size to those existing when the beach was considerably denuded. Furthermore, there have been no heavy rains since 1938 which could be expected to provide large supplies of sand for beach building. Erosion of the alluvial cliffs, which is probably another large source of sand for the beach, has been decreasing in recent years and has entirely stopped along two-thirds of the cliffed area because of the building of sea walls. Accordingly, there is no clearly evident cause of the growing stability of this beach. In addition to this increasing stability, the sand along Scripps pier is slightly shoaler than in former years and also the troughs and bars formerly found along the pier have not been detected in recent years (Shepard, 1949b).

Changes Associated with Engineering Structures

The unusual summer cut near the entrance to Mission Bay referred to previously is possibly the result of dredging in Mission Bay which strengthened the currents in the approaches to the bay. Continuing changes can be expected because of the building of the breakwaters connected with the new harbor and the San Diego River drainage channel. The extensive cutting reported in recent years at Oceanside may be associated with the jetties at Camp Pendleton to the north. A serious cut at Redondo in the Los Angeles area is the result of a breakwater which prevents introduction of sand from the north so that the cutting of winter storms is not replaced by a summer fill. The cutting is accentuated because the locality is just north of a submarine canyon head.

Relation of Beach Changes to Grain Size

Observations of the southern California beaches indicate that changes are much more rapid where the sand is coarse than where it is fine. The steep, high scarps are also confined to coarse sands. For example, the beaches around La Jolla Point which have sand averaging about 0.5 mm. in median diameter undergo much faster changes than do the long, fine-sand beaches like Scripps Beach and the beach at Mission Bay. The complete disappearance of the coarse sand of the northern portion of Boomer Beach in one storm has been mentioned previously.

As a cause for the rapid erosion of coarse sands we can point to the steep foreshore which causes the waves to break much closer to the berm edge. Also the backwash gathers more momentum running down the steep slopes than down the gentle slopes of fine sand beaches.

Conservation of Sand Supply

The observation of beach cycles, particularly in the La Jolla area where 15 years of observations are available, has shown that the beach is cut every winter and built up every summer without any evident decrease in the total sand. This is partially substantiated by profiles of the maximum cut and maximum fill along the Scripps

Institution pier over a period of 6 years (figure 15). Many of the beaches of California have been mapped with sufficient care by the Coast and Geodetic Survey for the past 50 or even 75 years to tell whether or not there is any large net change. Comparisons indicate that very little has happened during this period except where shifts have resulted from the building of jetties and other engineering structures. This conservation of the sand supply must indicate either that new sand is being added as fast as old is lost or that the same sand washed out during the winter is carried back during the summer.

Beaches like Boomer in La Jolla appear to have little source of new sand because there are no appreciable streams entering even during floods, the cliffs are being eroded very slowly (probably not more than an inch in 10 years) and the jutting rocky points on both sides prevent access of new supplies. Therefore, it appears virtually certain that the sand removed during the winter must return during the summer. It might be supposed that in an area where the prevailing direction of wave approach alternates with the season, the sand supply would be conserved provided that the components of wave energy along the beach from the two directions were approximately equal. Actually there are few, if any, areas in southern California where this condition exists. Boomer Beach, which faces northwest, may be an exception but even here the principal cause of sand conservation is probably the jutting headlands which prevent longshore migration. Elsewhere, along more open beaches, the southerly swell in summer probably balances only a part of the south drift coming from the northwest storms of winter. This is particularly true along portions of the coast extending east and west, such as the Santa Barbara area where the waves approach predominantly from one direction throughout the year. Therefore a large, new supply appears to be necessary to take the place of the sand drifted along the coast during the period of beach cutting. This is demonstrated by the disastrous effects of the building of the Santa Barbara breakwater. Shortly after it was built the beaches to the east became deeply eroded because the source of sand from the west was removed.

Permanent loss of sand from the beaches must occur also where submarine canyon heads extend in close to the coast. The repeated measurements of profiles at canyon heads show that fill is invariably followed by deepening (Shepard 1949b). Evidence from Redondo pier and from the pier at Moss Landing shows that the changes at the canyon heads are relatively rapid (Shepard and Emery, 1941, pp. 94-103), probably occurring as slides or "mud" flows of the accumulated sediment. This process carries material out to sea where it must certainly get beyond the reach of the shoreward push exerted by the waves during summer conditions. The introduction of new sand from an up-current area explains the persistence of the beaches in the canyon areas. During northwest storms large quantities of sand are carried south along the coast. After the storm waves have decreased, the portions of this sand which have not fallen into the canyon creep shoreward, building up the beaches. An indication of the importance of this source comes from Redondo where the construction of a breakwater cut off the sediment from the north of Redondo submarine canyon. As a result the sand which was carried into the canyon could not be replaced. The beach has been entirely removed at this point and deep water extends up to the shore which is protected by large blocks of rock.

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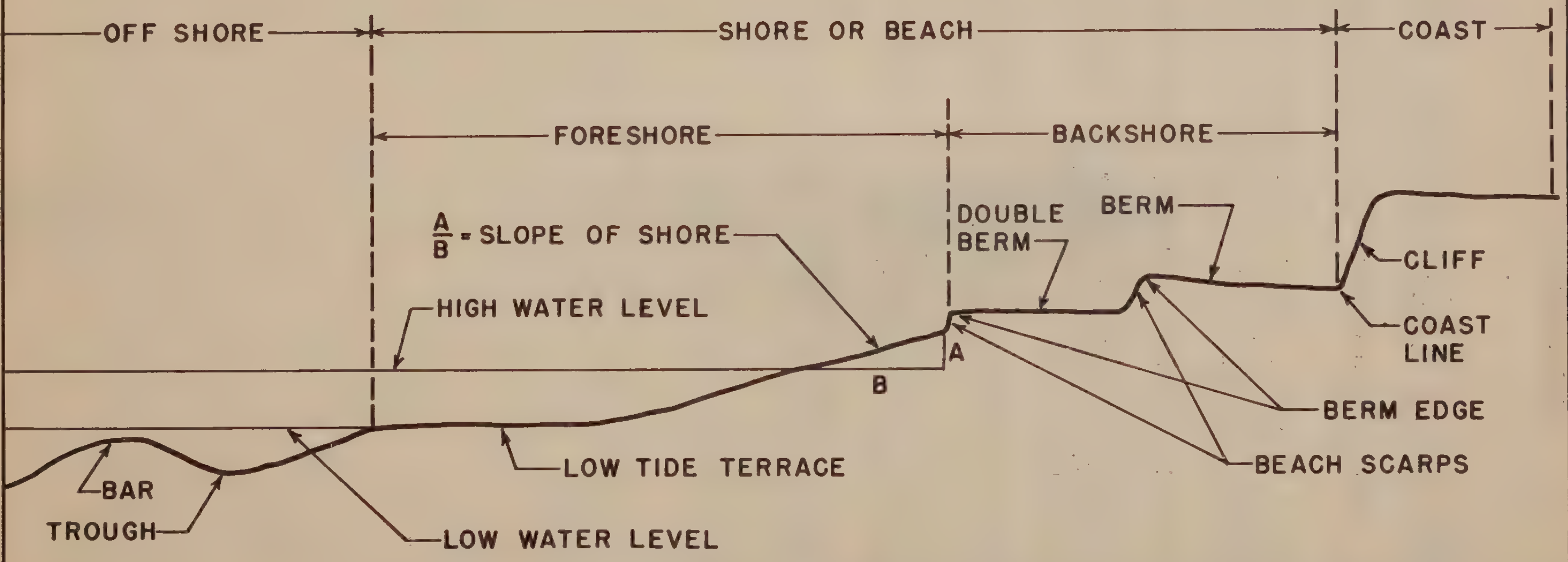
FIGURE I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SHORE OR BEACH
COAST
FORESHORE
BACKSHORE
$\frac{A}{B}$ = SLOPE OF SHORE
DOUBLE BERM
BERM
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LOW WATER LEVEL

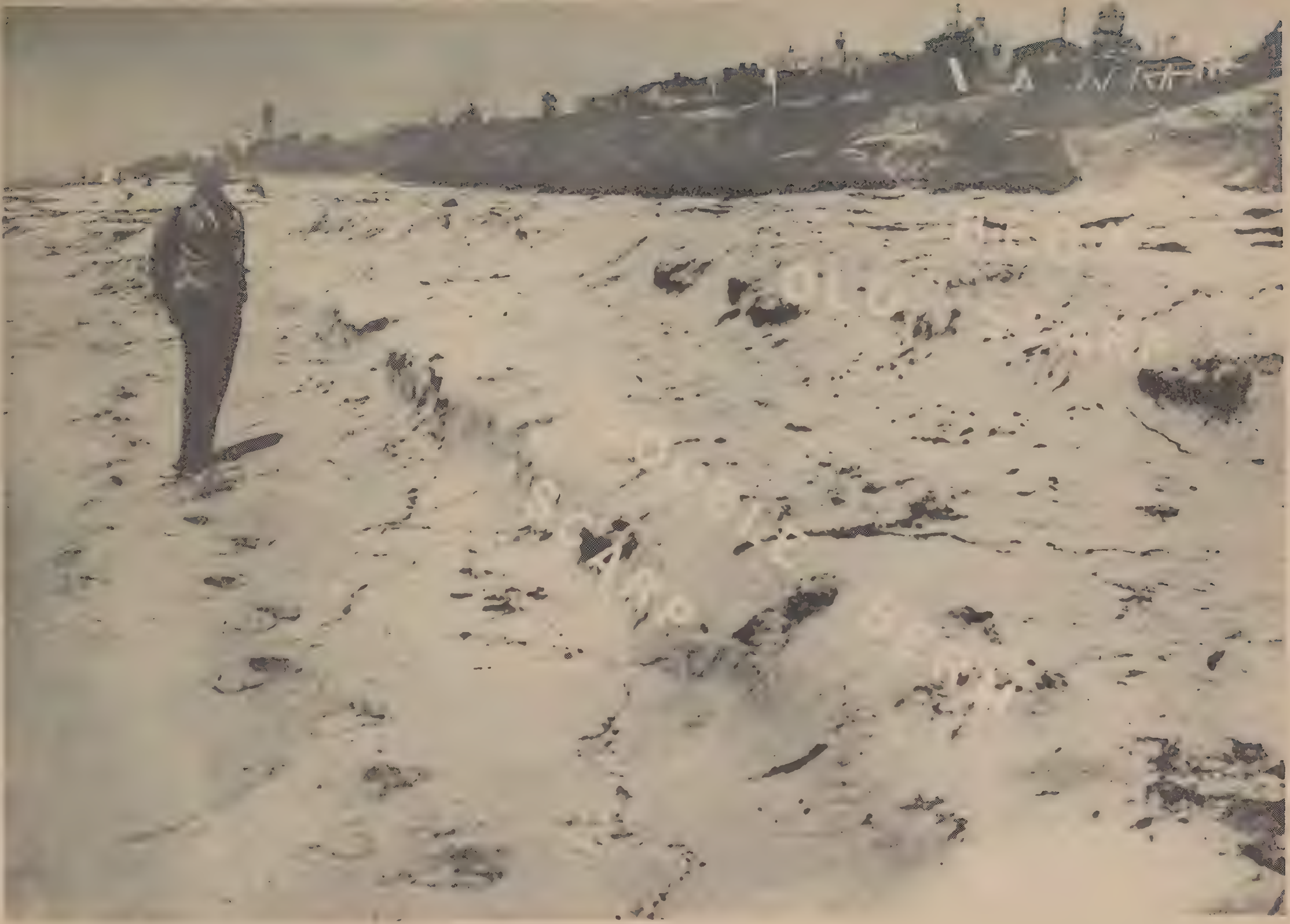
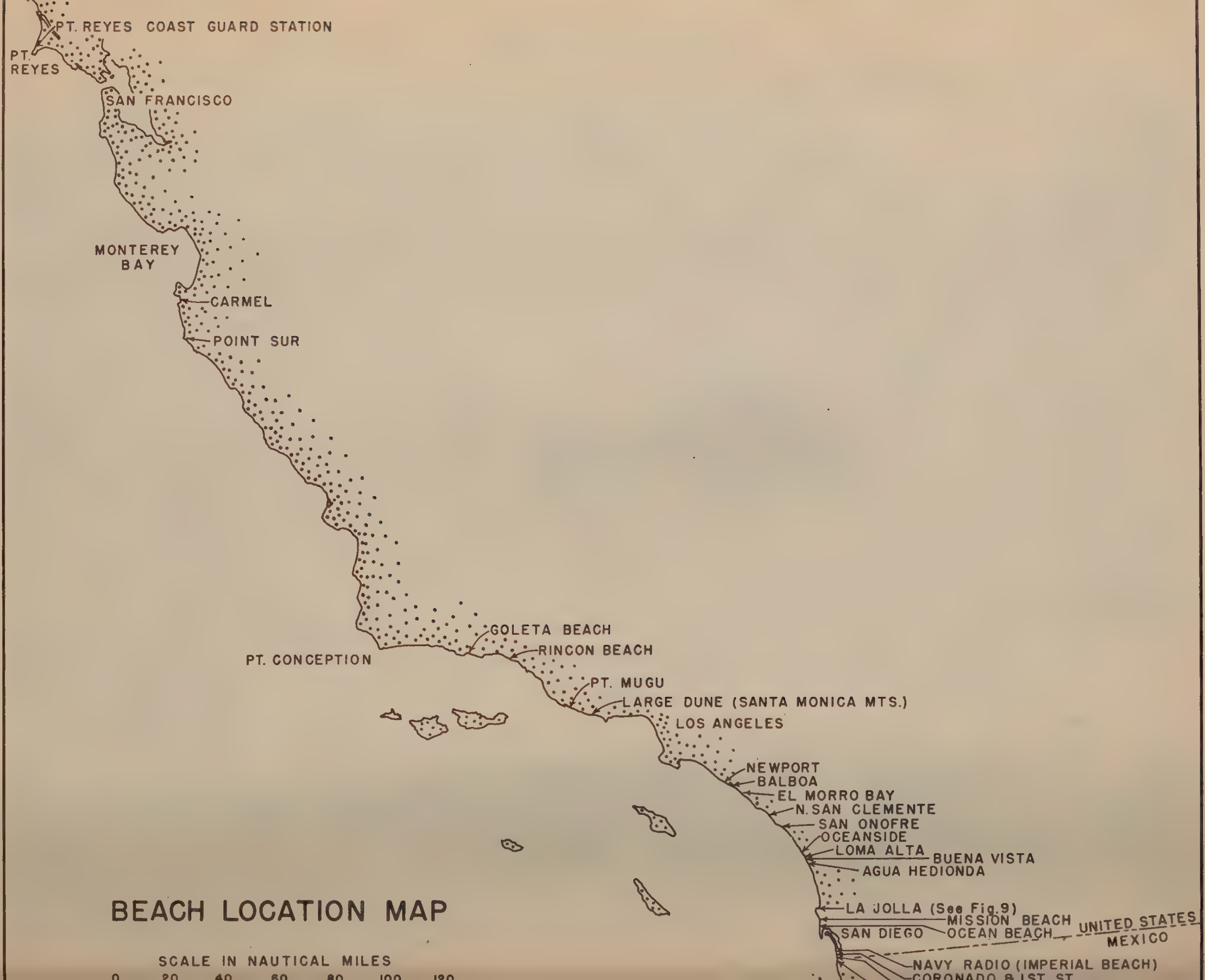
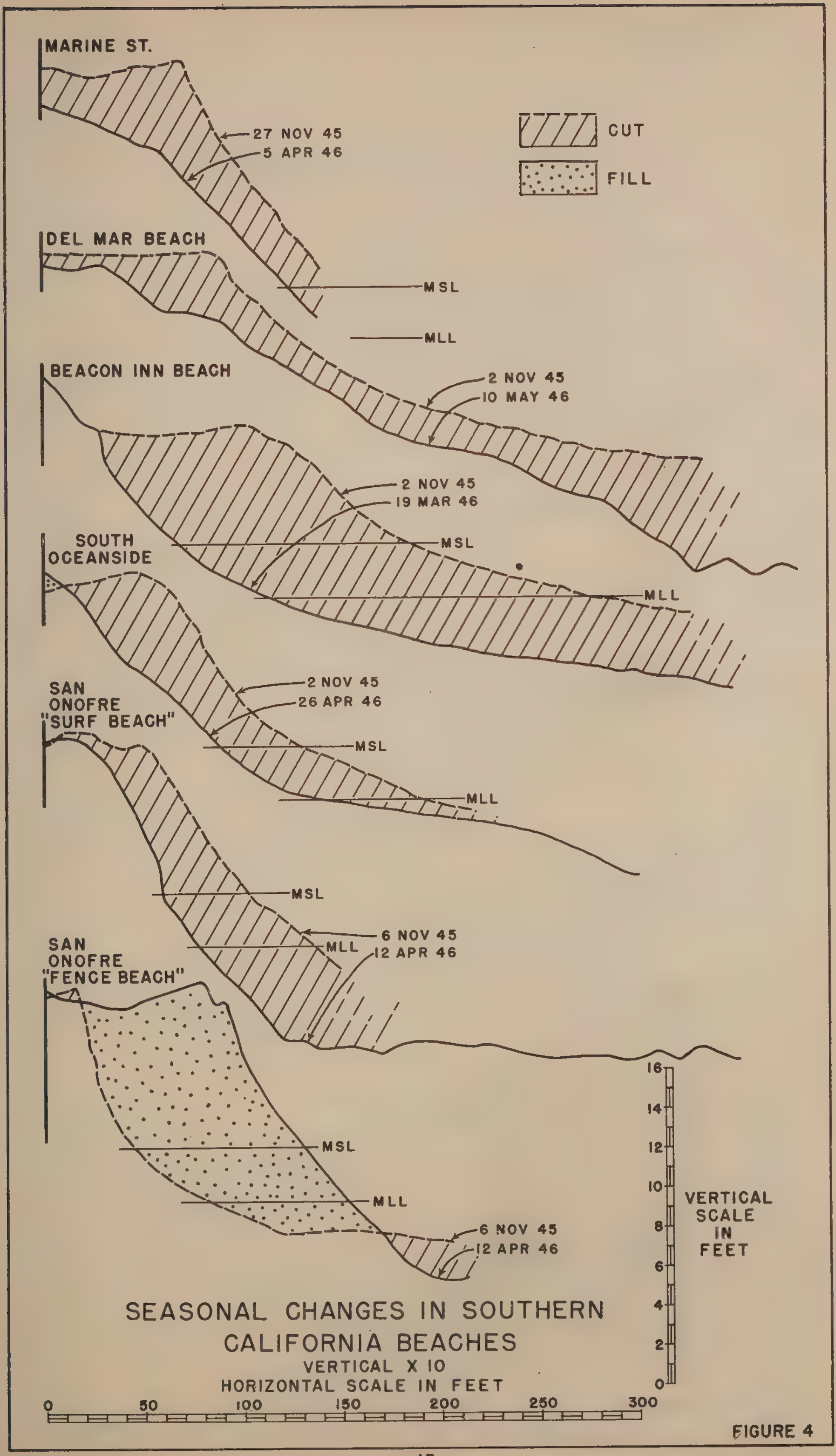

OLD SCARP
DOUBLE BERM
SCARP

FIGURE 2. SCARPS AND BERMS AT WINDANSEA BEACH. OLD SCARP LARGELY BURIED BY THE DOUBLE BERM AND LOWER SCARP FORMED SUBSEQUENTLY.



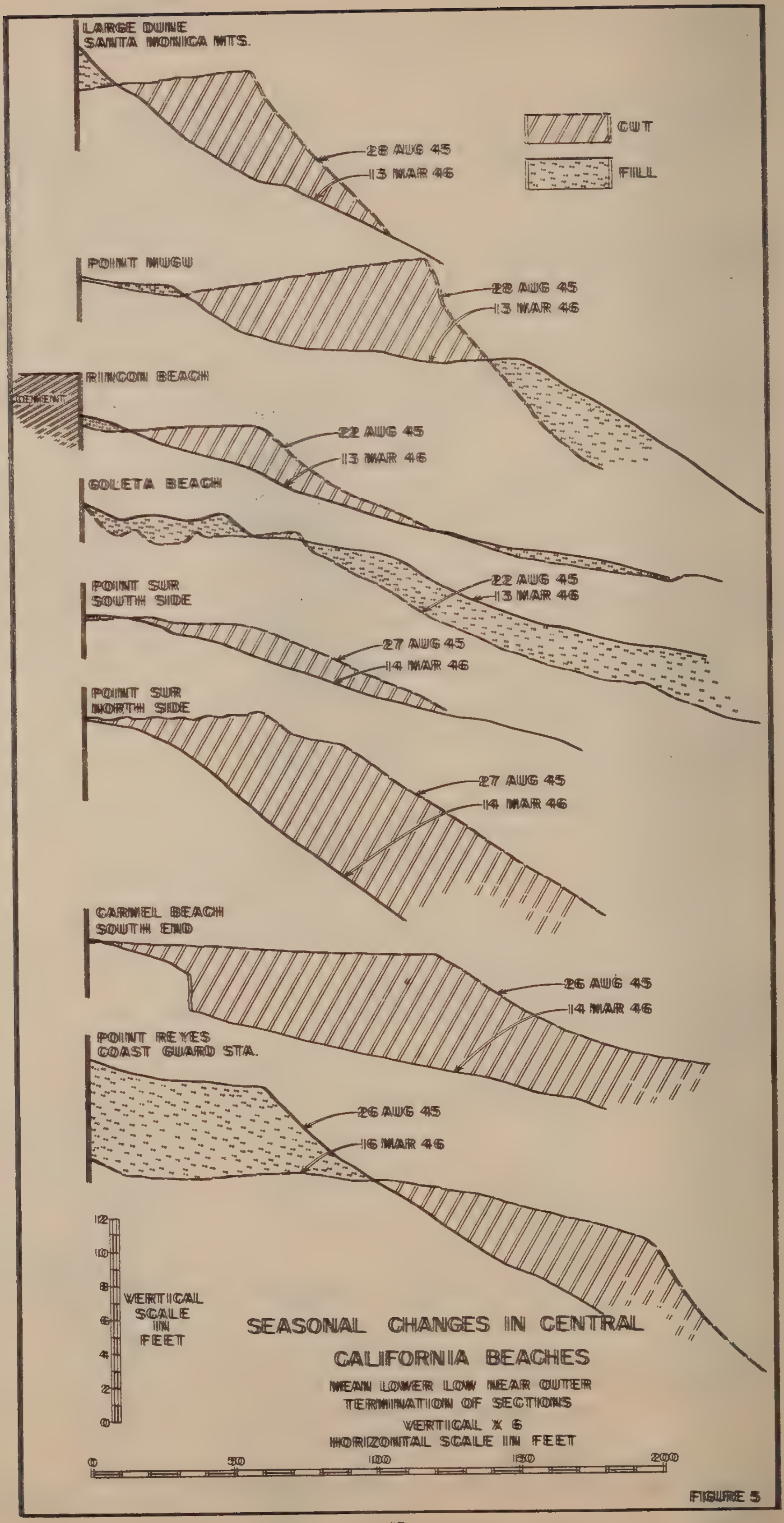
BEACH LOCATION MAP

PT. REYES COAST GUARD STATION
PT. REYES
SAN FRANCISCO
MONTEREY BAY
CARMEL
POINT SUR
PT. CONCEPTION
GOLETA BEACH
RINCON BEACH
PT. MUGU
LARGE DUNE (SANTA MONICA MTS.)
LOS ANGELES
NEWPORT
BALBOA
EL MORRO BAY
N. SAN CLEMENTE
SAN ONOFRE
OCEANSIDE
LOMA ALTA
BUENA VISTA
AGUA HEDIONDA
LA JOLLA (See Fig.9)
MISSION BEACH
SAN DIEGO
OCEAN BEACH
UNITED STATES
MEXICO
NAVY RADIO (IMPERIAL BEACH)
CORONADO & 1ST ST.
SCALE IN NAUTICAL MILES
0
20
40
60
80
100
120



SEASONAL CHANGES IN SOUTHERN CALIFORNIA BEACHES
VERTICAL X 10
HORIZONTAL SCALE IN FEET

FIGURE 4



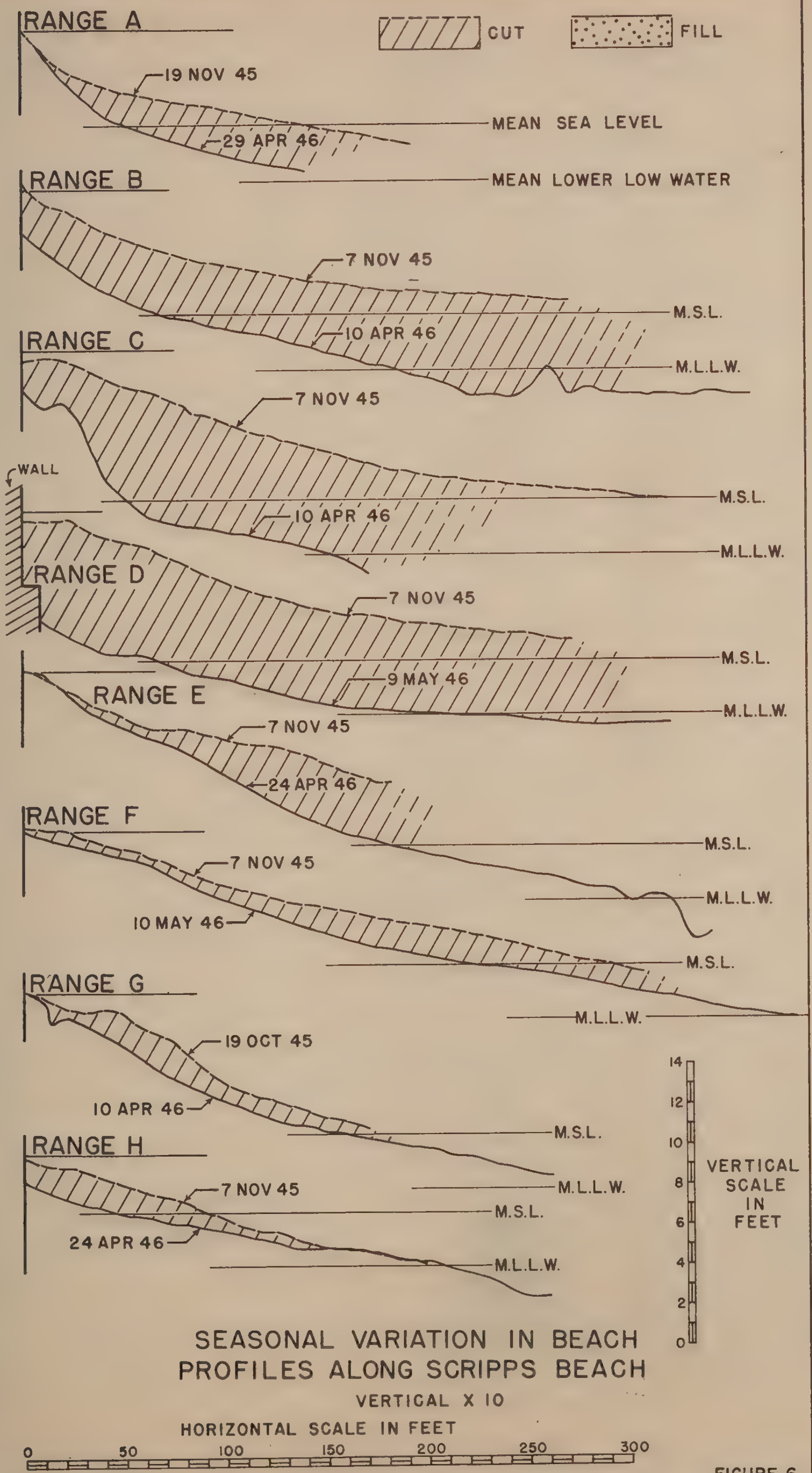
SEASONAL CHANGES IN CENTRAL CALIFORNIA BEACHES

MEAN LOWER LOW NEAR OUTER TERMINATION OF SECTIONS

VERTICAL X 6

HORIZONTAL SCALE IN FEET

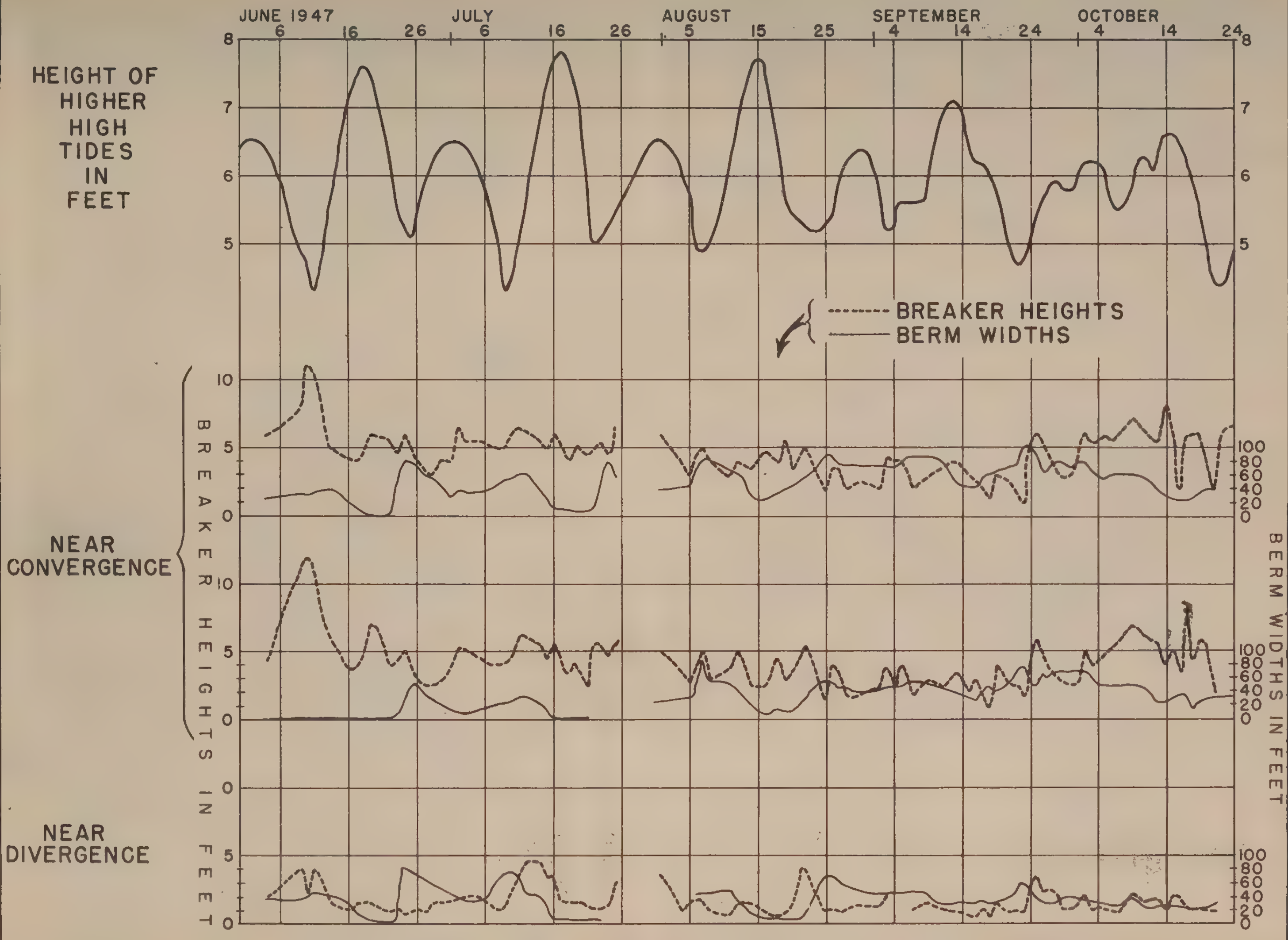
FIGURE 5



SEASONAL VARIATION IN BEACH PROFILES ALONG SCRIPPS BEACH

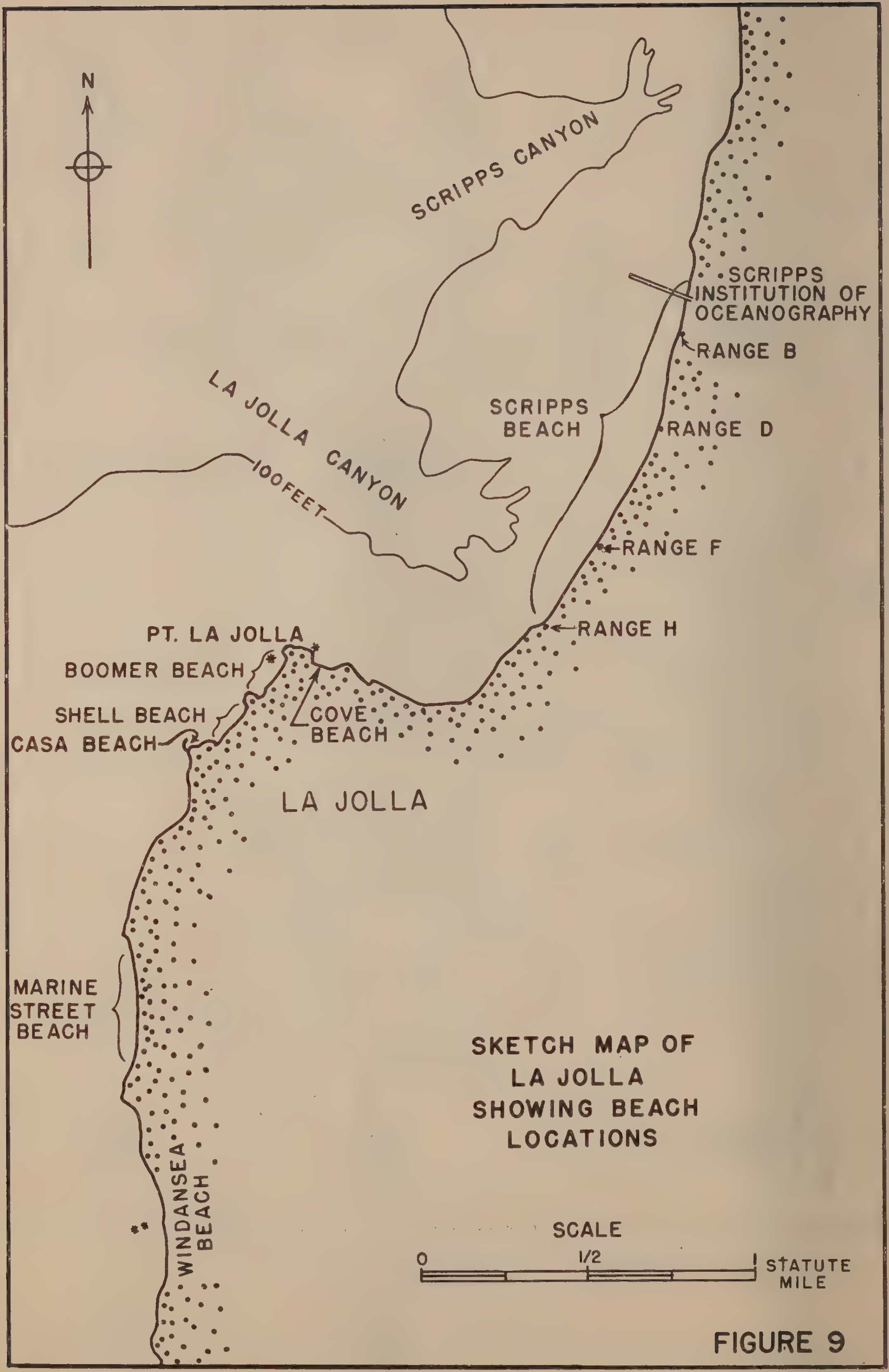
VERTICAL X 10

FIGURE 6



RELATION OF TIDE RANGE, BREAKER HEIGHT AND BERM WIDTHS

FIGURE 8


N
SCRIPPS CANYON
SCRIPPS INSTITUTION OF OCEANOGRAPHY
RANGE B
SCRIPPS BEACH
RANGE D
LA JOLLA CANYON
100 FEET
RANGE F
RANGE H
PT. LA JOLLA
BOOMER BEACH
SHELL BEACH
COVE BEACH
CASA BEACH
LA JOLLA
MARINE STREET BEACH
WINDANSEA BEACH
SCALE
0
1/2
1
STATUTE MILE

SKETCH MAP OF LA JOLLA SHOWING BEACH LOCATIONS

FIGURE 9

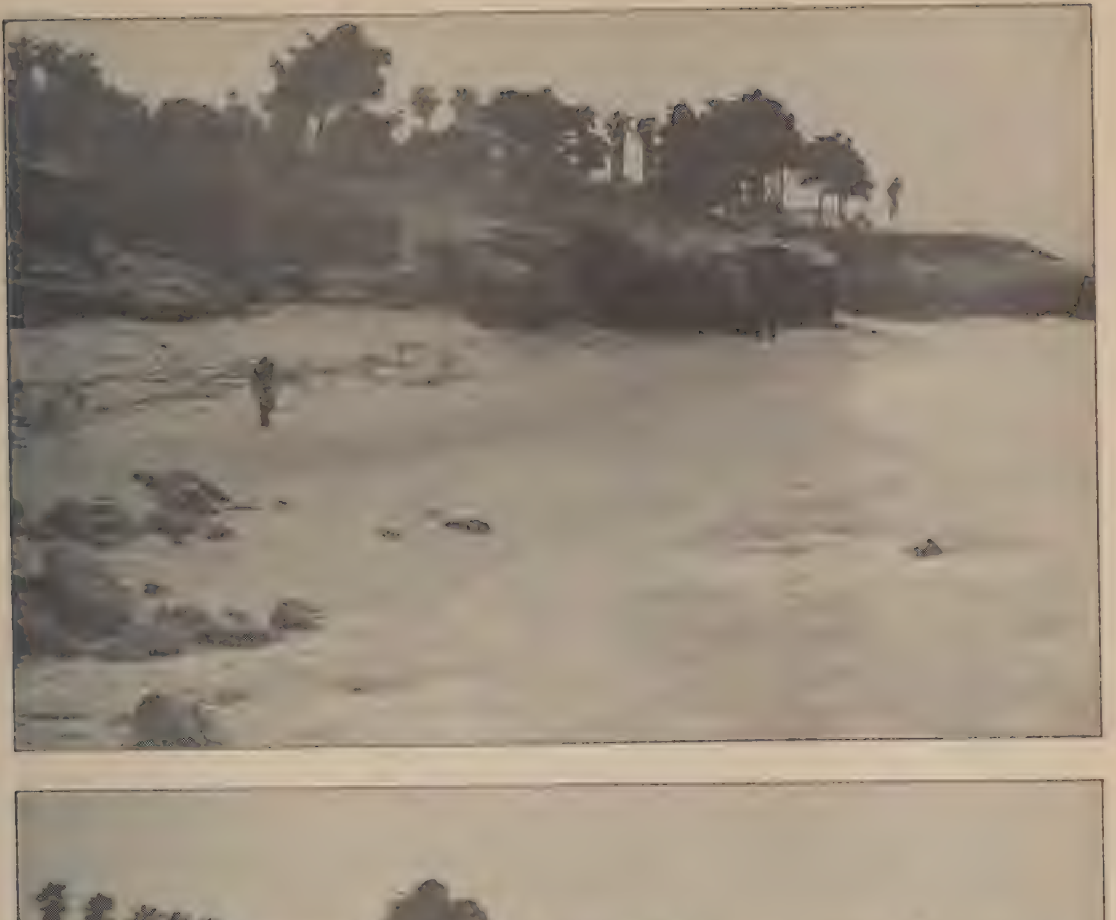
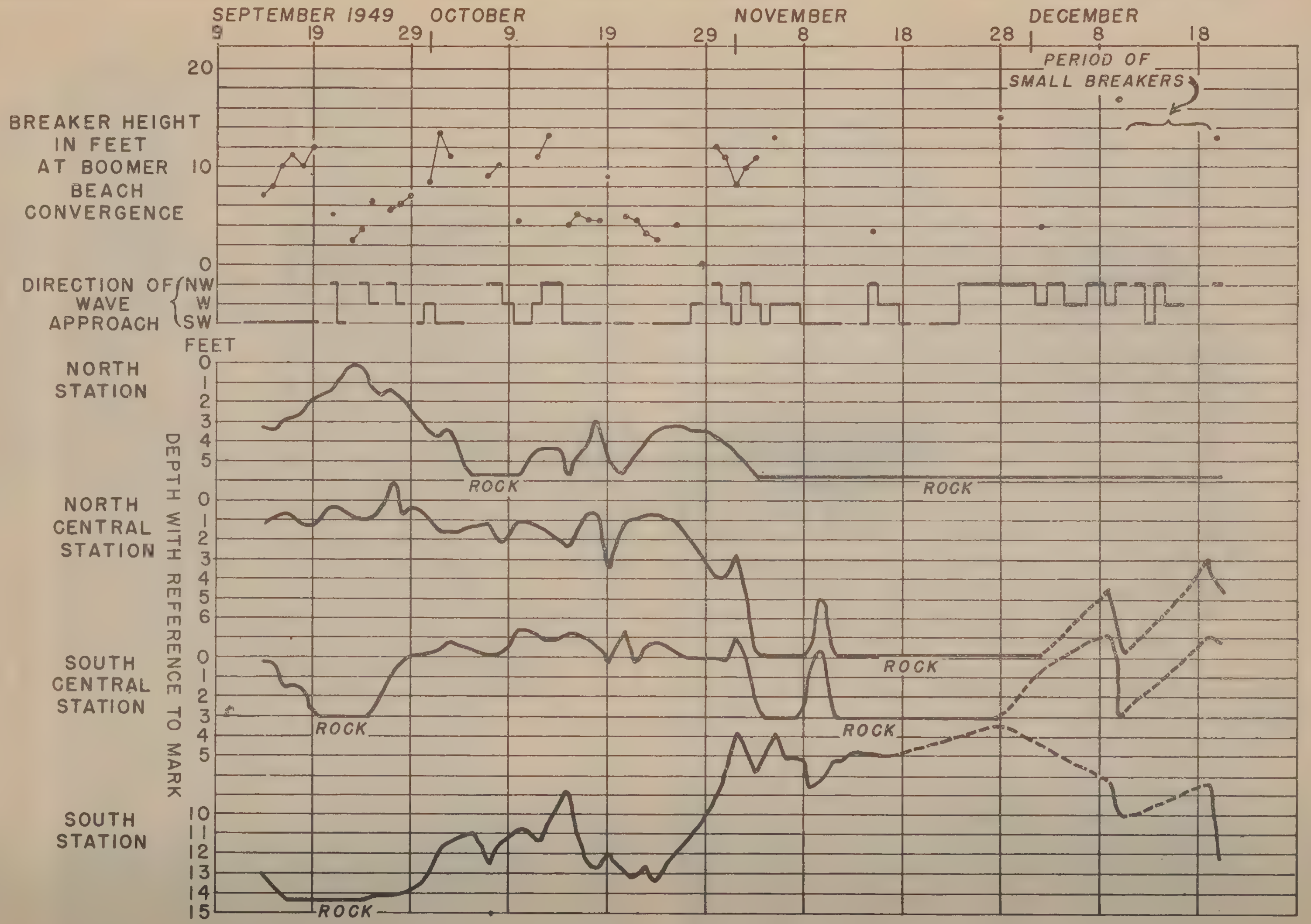
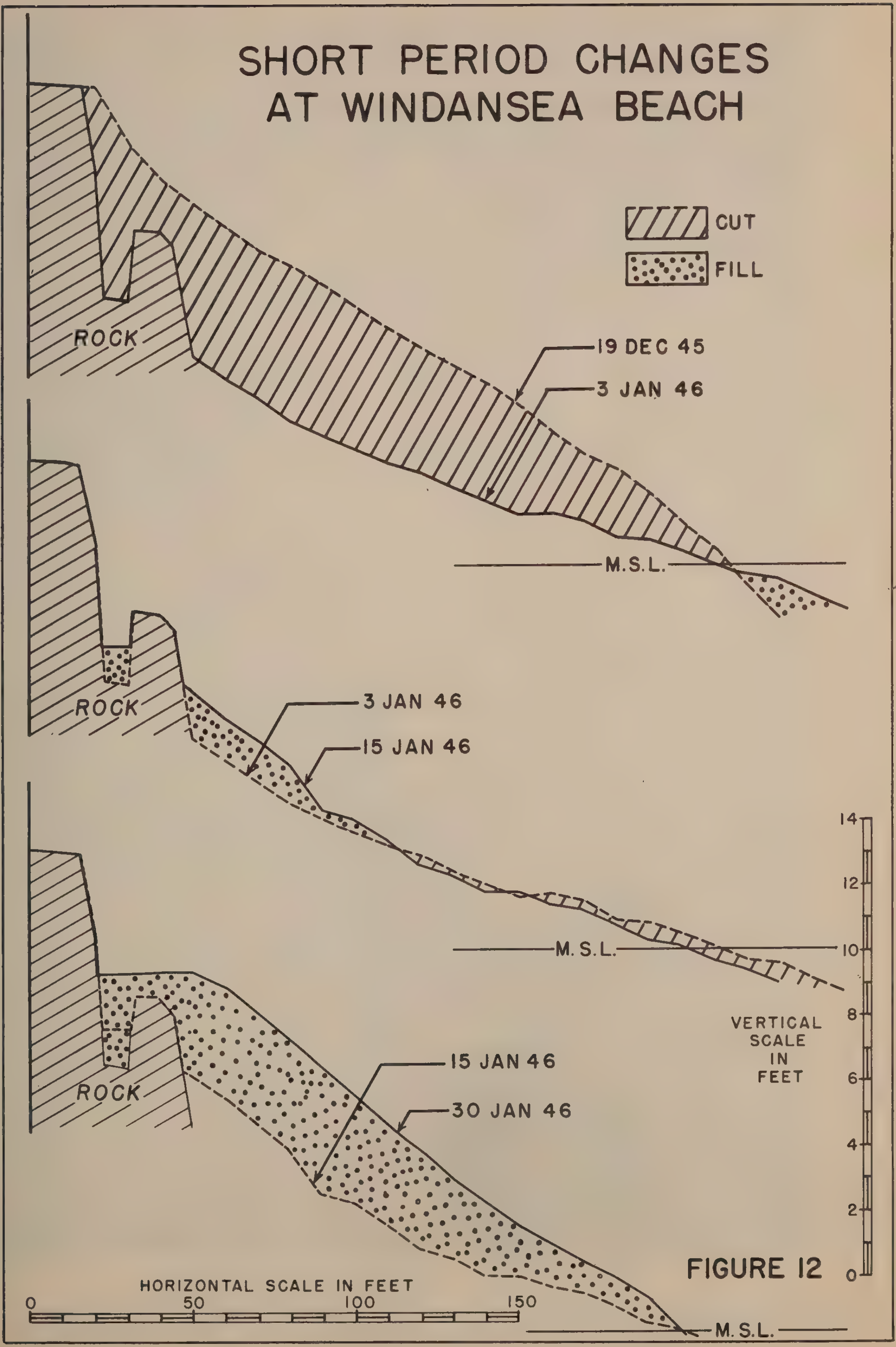


FIGURE 10. SOUTH END OF BOOMER BEACH UNDER CONDITION OF SOUTHWEST WAVE APPROACH (TOP PHOTO) AND NORTHWEST APPROACH (BOTTOM PHOTO.)

FIGURE 11



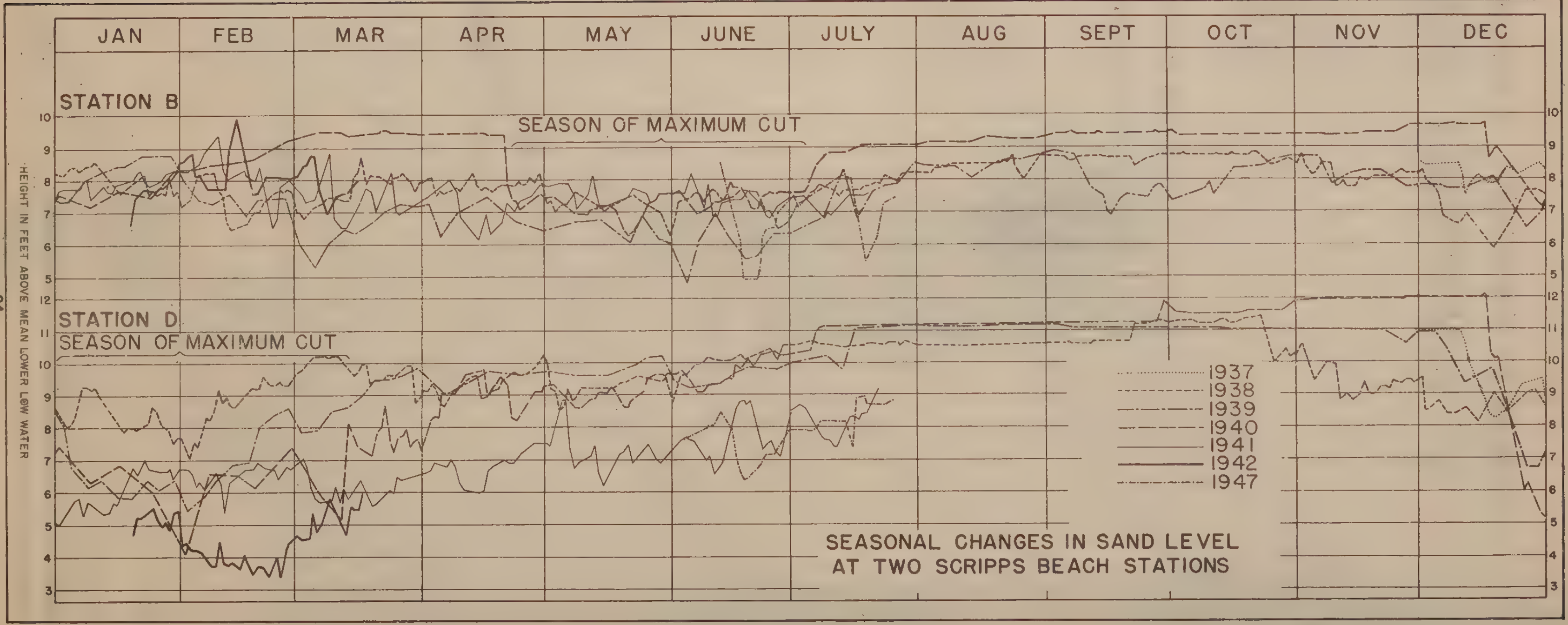
CUT AND FILL AT BOOMER BEACH IN RELATION TO WAVE APPROACH AND BREAKER HEIGHT



SHORT PERIOD CHANGES AT WINDANSEA BEACH

FIGURE 12

FIGURE 13



SEASONAL CHANGES IN SAND LEVEL
AT TWO SCRIPPS BEACH STATIONS

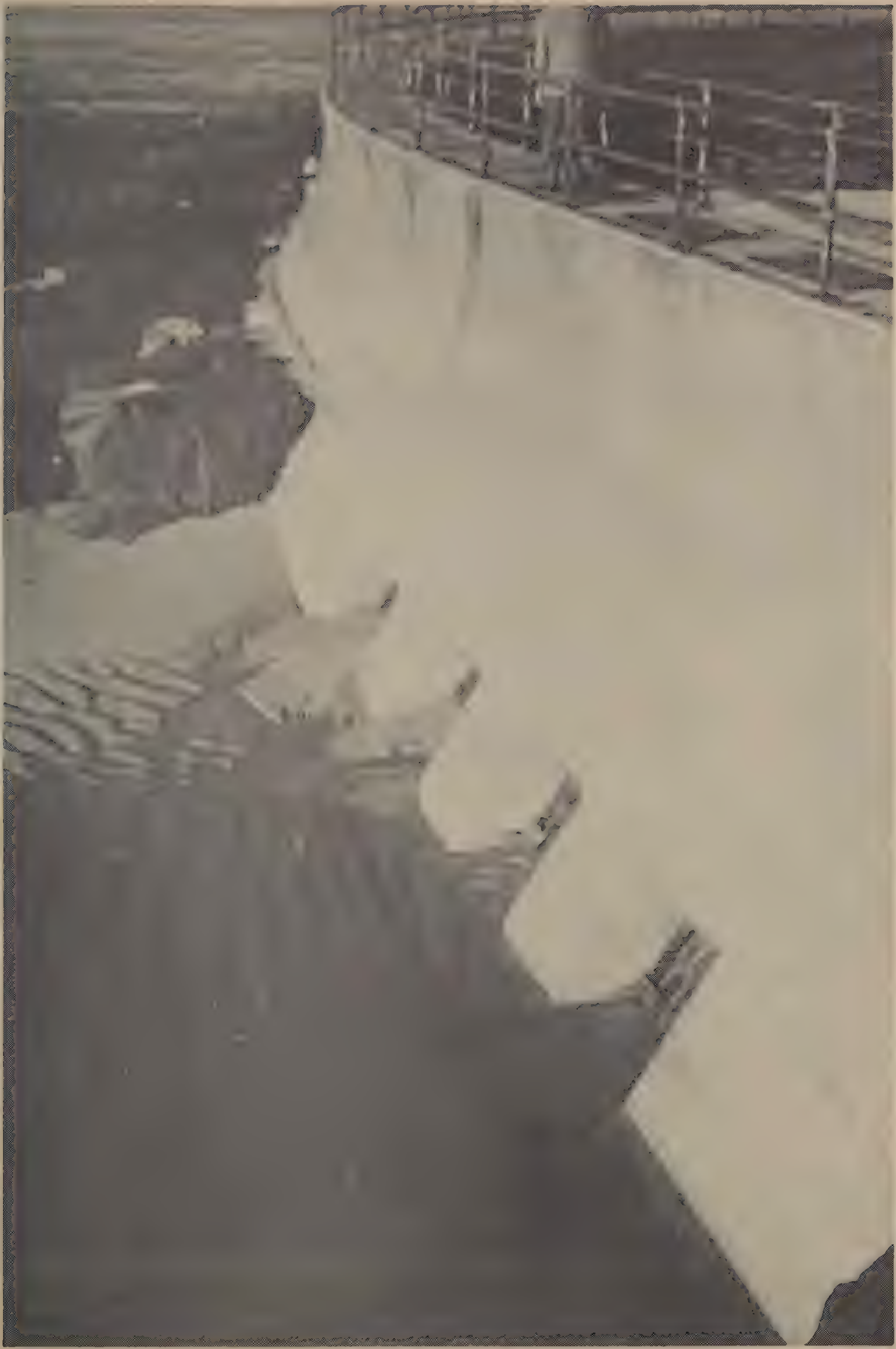


FIGURE 14. SOUTH SIDE OF SEA WALL AT CASA POOL WITH SAND CUT LOW ENOUGH TO EXPOSE SLUICES. NORMALLY, THE SAND IS BUILT UP NEARLY TO TOP OF WALL.

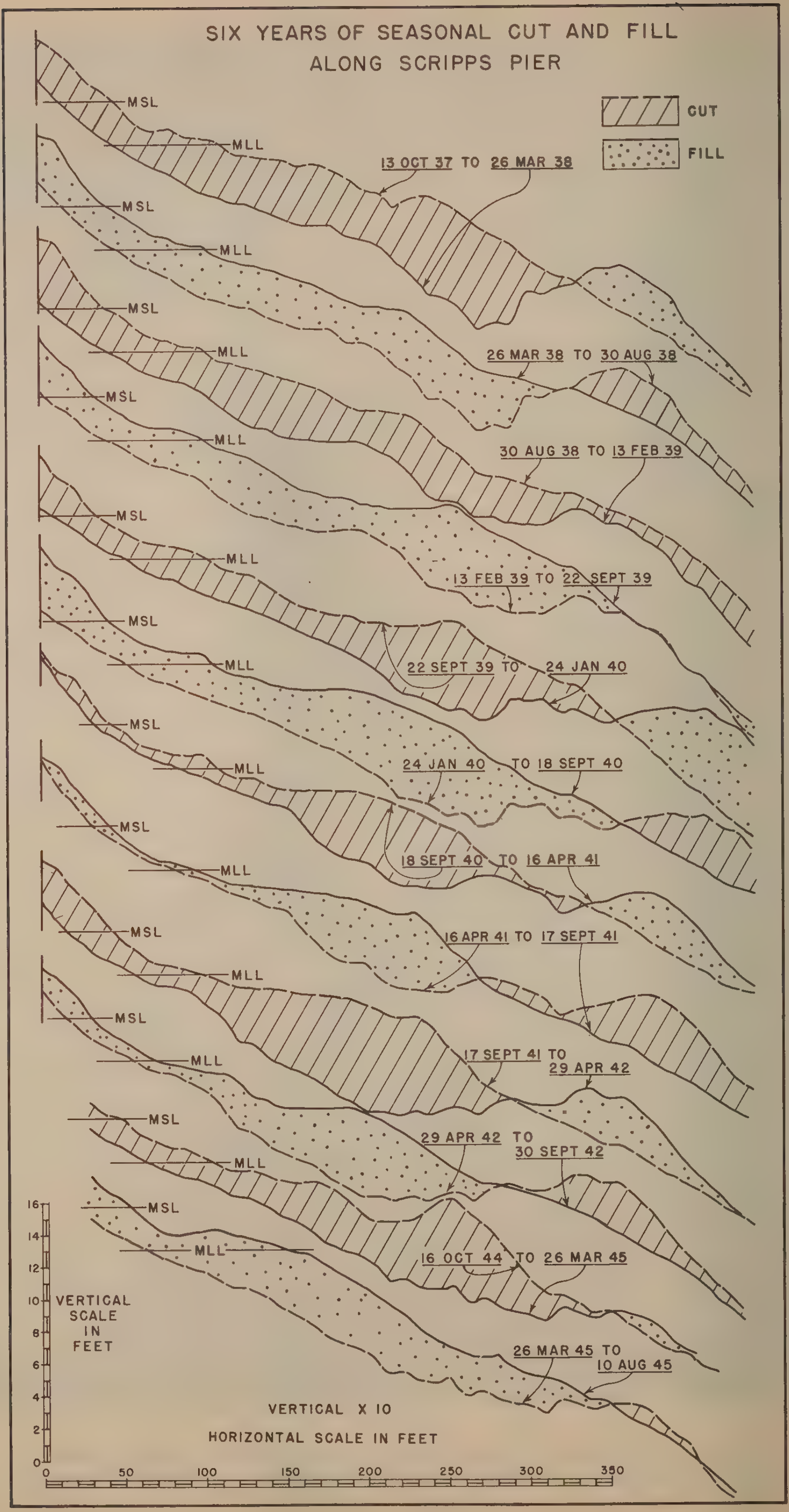

SIX YEARS OF SEASONAL CUT AND FILL
ALONG SCRIPPS PIER
CUT
FILL
MSL
MLL
13 OCT 37 TO 26 MAR 38
26 MAR 38 TO 30 AUG 38
30 AUG 38 TO 13 FEB 39
13 FEB 39 TO 22 SEPT 39
22 SEPT 39 TO 24 JAN 40
24 JAN 40 TO 18 SEPT 40
18 SEPT 40 TO 16 APR 41
16 APR 41 TO 17 SEPT 41
17 SEPT 41 TO 29 APR 42
29 APR 42 TO 30 SEPT 42
16 OCT 44 TO 26 MAR 45
26 MAR 45 TO 10 AUG 45
VERTICAL SCALE IN FEET
0
2
4
6
8
10
12
14
16
VERTICAL X 10
HORIZONTAL SCALE IN FEET
0
50
100
150
200
250
300
350

FIGURE 15

Contribution No. 475

SOUTHERN HEMISPHERE SWELL AND WAVES FROM A TROPICAL STORM AT LONG BEACH, CALIFORNIA

BY

PAUL L. HORRER
Scripps Contribution No. 475

Reprint from Beach Erosion Bulletin
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THE BULLETIN OF THE BEACH EROSION BOARD

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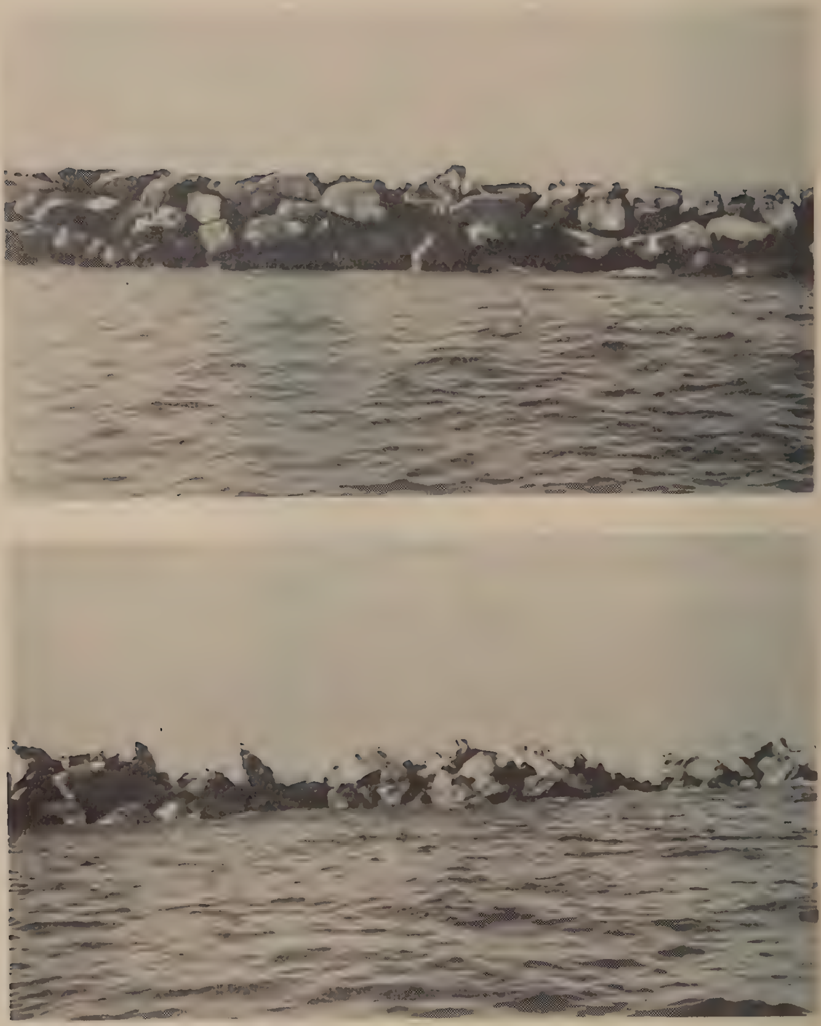


FIGURE I. THE RELATIVELY UNDAMAGED WESTERN PART AND THE DAMAGED EASTERN PART OF THE LOS ANGELES-LONG BEACH DETACHED BREAKWATER AFTER WAVE ACTION OF SEPTEMBER 1939.

SOUTHERN HEMISPHERE SWELL AND WAVES FROM A TROPICAL STORM AT LONG BEACH, CALIFORNIA

This paper is published as a companion piece to the paper, "Wave Refraction at Long Beach and Santa Barbara, California", by M. P. O'Brien, published in the Beach Erosion Board Bulletin, Vol. 4, No. 1, January 1950. The paper was prepared by Paul L. Horrer and represents results of research carried out for the Hydrographic Office and the Office of Naval Research of the Department of the Navy under contract with the University of California. Scripps Contribution No. 475.

Introduction

On two occasions nine years apart large waves entered San Pedro Bay and caused extensive damage to the harbor breakwaters in the Long Beach-San Pedro area. During the period April 20 to 24, 1930, intensive wave action resulted in the displacement of 20,000 tons of superstructure stone from the Long Beach breakwater. On September 24 and 25, 1939, large waves caused some damage to the San Pedro Breakwater and great damage to the Los Angeles-Long Beach Detached Breakwater (Figure 1). The present study was undertaken in an attempt to analyze the meteorological conditions which produced the damaging wave action in this region and to provide information which may be used in planning future modification and improvement of the breakwaters.

As indicated by O'Brien (1947) it seems impossible that waves from westerly directions could bring sufficient concentration of wave energy to effect material damage to these breakwaters. Except for a narrow exposed western sector between Santa Rosa and Santa Barbara Islands all swell from the west must undergo diffraction and such great refraction around islands that little energy can reach this portion of San Pedro Bay. The only unsheltered directions of approach for swell lie within a wider sector to the south between the coast and the islands of Santa Catalina and San Clemente. Two distinct types of waves which could damage the breakwaters may enter through this exposed southern sector. These are swell propagated from storms in the southern hemisphere and wind waves or swell produced by northern hemisphere storms located south of Long Beach. It is necessary to stress the importance of each type separately.

The synoptic weather maps for the critical period in April, 1930 do not reveal any northern hemisphere storm which could generate large waves or swell which would pass through the exposed southern sector. This leaves only the possibility of a long, low swell from a storm in the southern hemisphere. Refraction diagrams (Figures 2-5) have been constructed for San Pedro Bay according to the procedure given by Munk and Traylor (1947). These diagrams indicate that San Pedro Shelf, the submarine plateau due south of Long Beach, very effectively converged swell from the south upon certain portions of the Long Beach Breakwater, which with the San Pedro Breakwater formed the two principal structures protecting the harbor in 1930.

The intensive wave action which resulted in damage to the breakwaters in 1939 was derived from a tropical storm in the northern hemisphere. The characteristics of these waves differed materially from those of the swell which caused the damage in 1930. Therefore, the remainder of this discussion is divided into two parts: (1) southern hemisphere swell, and (2) waves from a tropical storm.

Part I - Southern Hemisphere Swell

The refraction of southern hemisphere swell has been examined for directions of approach of 170°, 180°, and 190° using a wave period of 20 seconds. For all three directions refraction diagrams were first constructed on small-scale charts showing San Clemente and Santa Catalina Islands and the approaches to San Pedro Bay (Figure 2). This type of presentation gives an overall picture of the bay's protection from, or exposure to, swell from given directions. Figure 2 is drawn for 190°, which is approximately the westernmost limit of the exposed southern sector from which southern hemisphere swell can converge upon the breakwaters. From directions west of 190° the zone of convergence shifts to the east of the outer breakwater.

The influence of the islands upon swell from direction 190° is illustrated by the extreme divergence of orthogonals a and b in Figure 2. In contrast to this, the portions of the wave crest unaffected by the islands between orthogonals c and e converge in crossing San Pedro Shelf. The waves passing both sides of the islands are refracted around the islands and meet to form a confused, crisscross pattern in the lee. Only the crests of the waves traveling around the east side of the islands have been drawn up to the breakwater. The waves traveling around the west side experience much greater divergence and contain negligible intensity of energy after refraction.

The boundary around San Pedro Bay in Figure 2 denotes the area covered by the detailed refraction diagrams presented in Figures 3-5. These large-scale diagrams were constructed using a crest interval of one wave period. The wave crests have been completed only up to the outer breakwater. In order to show quantitatively the intensity of wave energy for the wave crests at the breakwater and adjacent beaches bar graphs have been drawn. The lengths of the bars are proportional to the refraction factors according to the scale in the legend. The refraction factors have been computed assuming breaking waves only where the bars are located on the beaches west and east of the breakwater.

The detailed refraction diagram for 190° (Figure 3) shows divergence at the western part of the outer breakwater resulting primarily from the effect of refraction around San Clemente and Santa Catalina Islands. This island effect is accentuated by refraction over San Pedro Sea Valley, the

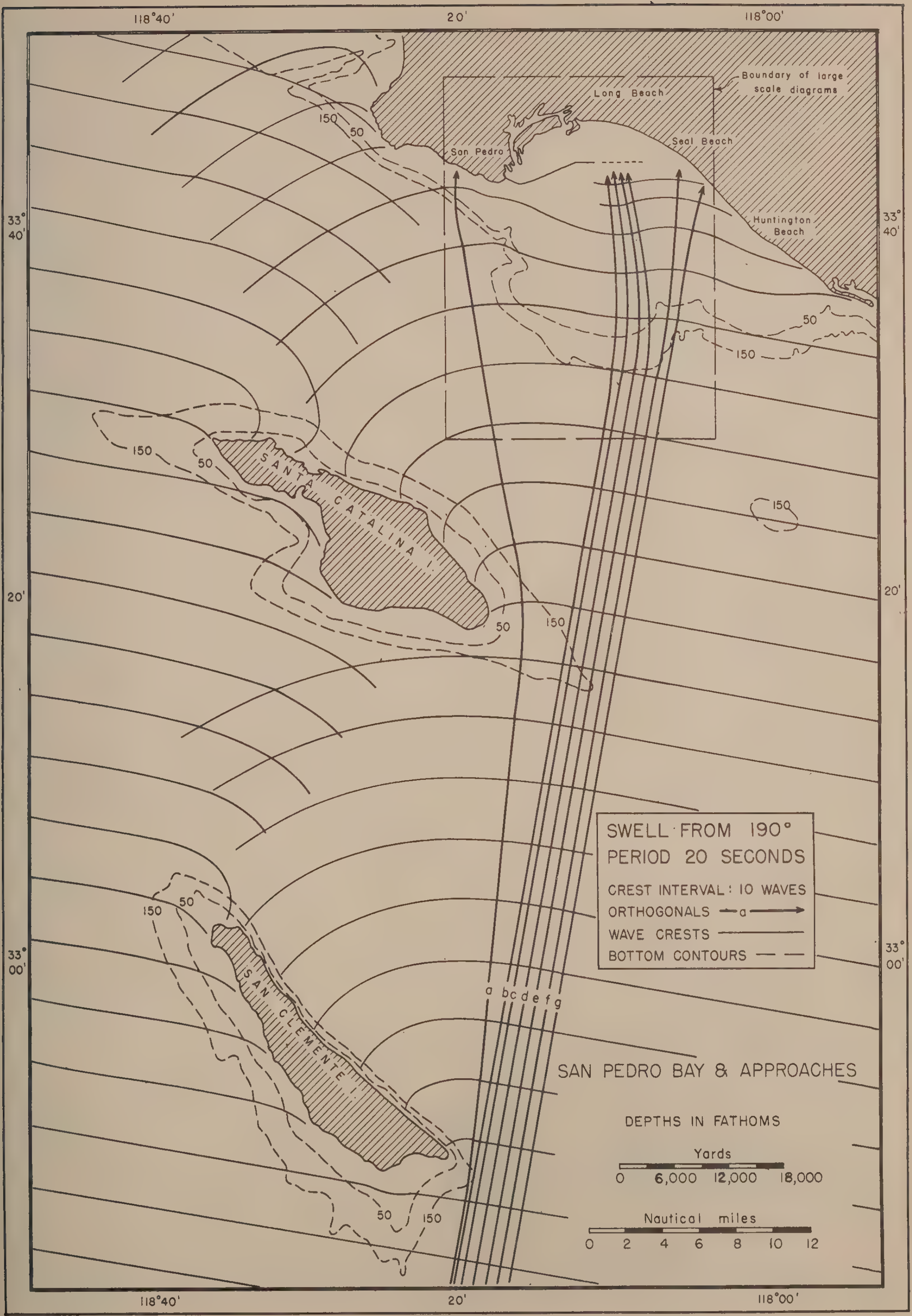

118°40'
20'
118°00'
Boundary of large scale diagrams
Long Beach
San Pedro
Seal Beach
Huntington Beach
33° 40'
20'
33° 00'
150
50
SANTA CATALINA I.
SAN CLEMENTE I.
a b c d e f g
SWELL FROM 190°
PERIOD 20 SECONDS
CREST INTERVAL: 10 WAVES
ORTHOGONALS —a—→
WAVE CRESTS ———
BOTTOM CONTOURS — —
SAN PEDRO BAY & APPROACHES
DEPTHS IN FATHOMS
Yards
0 6,000 12,000 18,000
Nautical miles
0 2 4 6 8 10 12

FIGURE 2

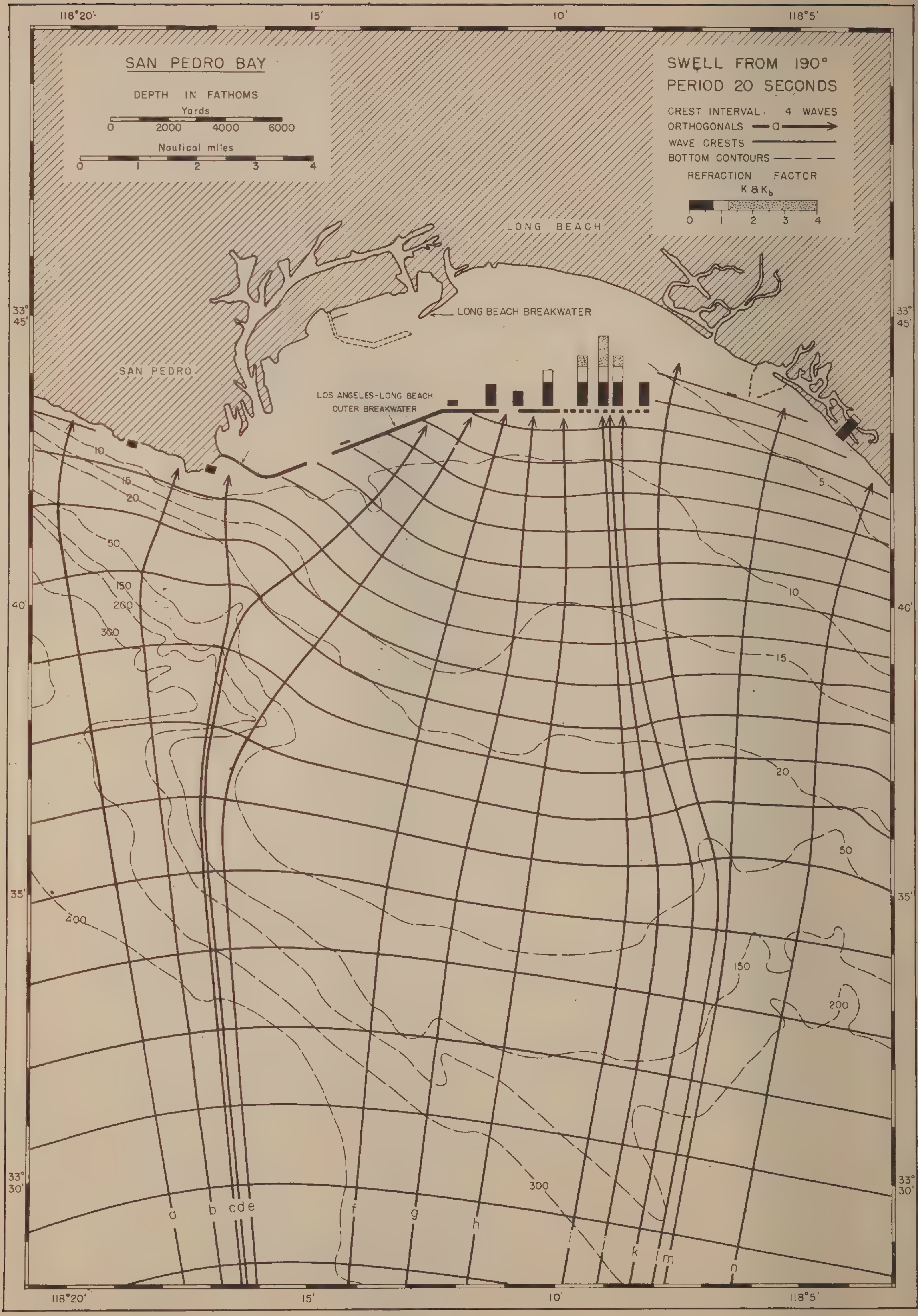

SAN PEDRO BAY
DEPTH IN FATHOMS
Yards
0 2000 4000 6000
Nautical miles
0 1 2 3 4
SWELL FROM 190°
PERIOD 20 SECONDS
CREST INTERVAL 4 WAVES
ORTHOGONALS a
WAVE CRESTS
BOTTOM CONTOURS
REFRACTION FACTOR
K & K_b
0 1 2 3 4
118°20'
15'
10'
118°5'
33° 45'
33° 40'
33° 35'
33° 30'
LONG BEACH
SAN PEDRO
LONG BEACH BREAKWATER
LOS ANGELES-LONG BEACH OUTER BREAKWATER
10
15
20
50
150
200
300
400
5
10
15
20
50
150
200
300
a
b
c d e
f
g
h
i
j
k
l
m
n

FIGURE 3

submarine valley located south of San Pedro, and leads to a maximum divergence between orthogonals c and d. Due to the focusing of wave energy by San Pedro Shelf, the wave crests between orthogonals g and k converge on the eastern portion of the breakwater, the greatest convergence occurring between i and j. On both sides of the breakwater the refraction factors indicate divergence.

Figures 4 and 5 show the detailed refraction diagrams for southern hemisphere swell advancing toward San Pedro Bay from 180° and 170° respectively. Although the main features of these figures are similar to those of Figure 3, several significant differences exist. These variations are shown best in Figure 6 which gives the refraction factors along the breakwater for all three diagrams. In addition, the refraction factors are plotted for 20 second waves from 160° as computed from the diagram presented by O'Brien (1947).

Figure 6 shows that an eastward shift in the direction of wave approach causes the zone of convergence to shift westward along the breakwater. The westward shift of the general pattern of wave refraction for 160° beyond that of 170° serves to support this. In the region of greatest divergence along the western portion of the breakwater greater intensity of wave energy is experienced from 160° than from the other three directions because the shadowing effect of the islands is lacking for 160°. In this connection the combined effects of the islands and San Pedro Shelf in shifting the entire refraction pattern may be compared to the action of a fulcrum, about which the wave approach and wave advance are pivoted.

The region of convergence indicated for directions of wave approach from 160° to 170° coincides closely with the location of the damaged portion of the Long Beach Breakwater in 1930. Applying a refraction factor of 3.50 for this zone of convergence and utilizing the available observations[1] of wave height, which were made during this critical period at locations seaward of the outer end of the breakwater, a deep water wave height of between 3 and 4 feet is obtained.

For southern hemisphere swell of 20 second period the refraction factor would be somewhat modified for slightly different period swell; shorter wave periods would be accompanied by less convergence.

Part II - Waves from a Tropical Storm.

The large waves at San Pedro Bay on September 24 and 25, 1939, were produced by unusually strong winds in the area of the North Pacific to the south of Long Beach. Unlike southern hemisphere swell which originates beyond the present weather reporting area, these waves could be estimated in advance by using available synoptic weather data. In this study the wave characteristics at San Pedro Bay have been computed for September 24 and 25 by use of the forecasting technique given by Francis (1944) and a set of wave forecasting graphs prepared by Arthur (1948) from the revised theory given by Sverdrup and Munk (1947).

Investigation of synoptic weather situation. - When the tropical storm appeared on the weather maps it was progressing northward along the

[1] All footnotes are given at the end of the article.

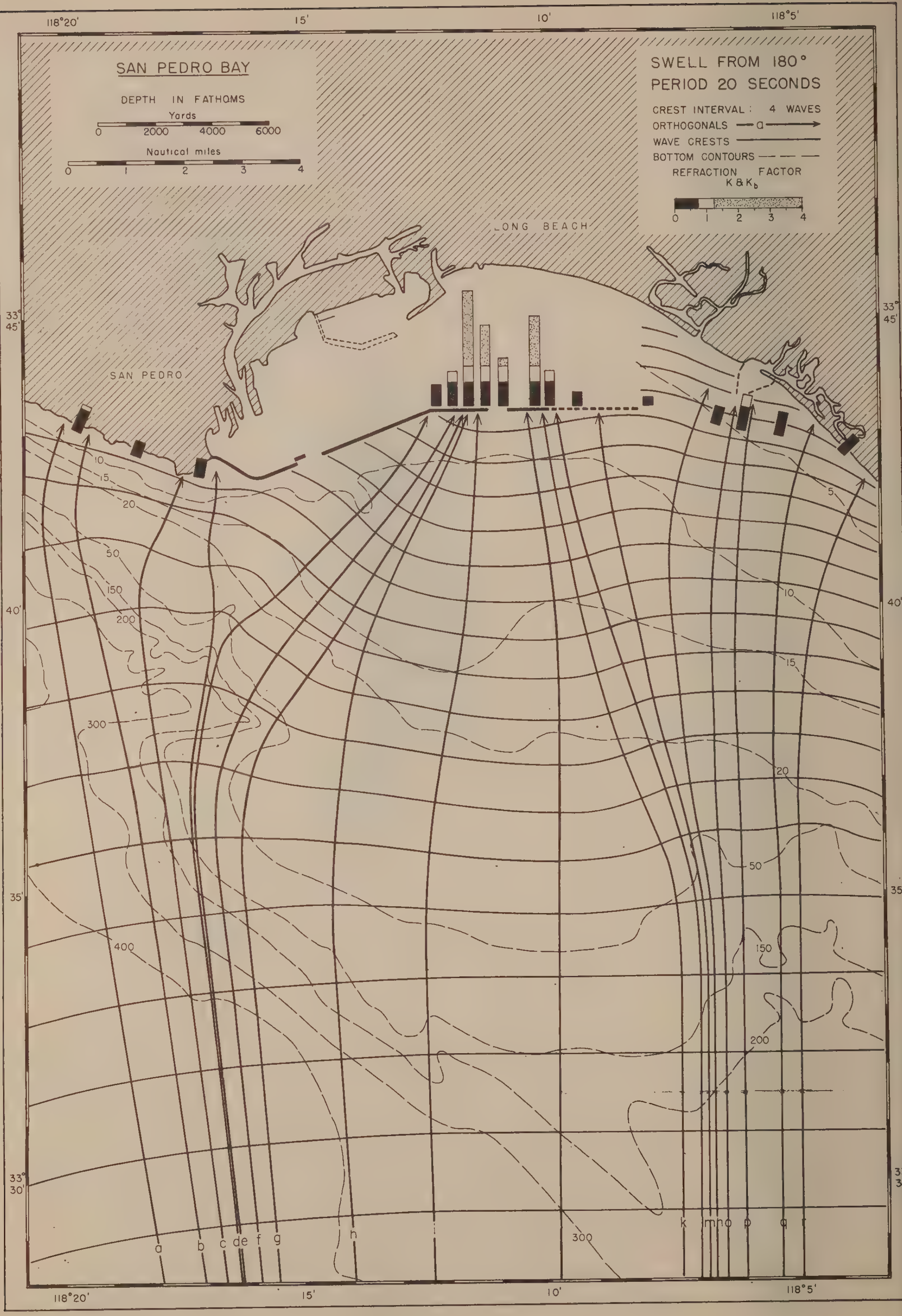

SAN PEDRO BAY
DEPTH IN FATHOMS
Yards
0 2000 4000 6000
Nautical miles
0 1 2 3 4
SWELL FROM 180°
PERIOD 20 SECONDS
CREST INTERVAL: 4 WAVES
ORTHOGONALS —a→
WAVE CRESTS
BOTTOM CONTOURS — — —
REFRACTION FACTOR
K & K_b
0 1 2 3 4
LONG BEACH
SAN PEDRO
118°20'
15'
10'
118°5'
33° 45'
40'
35'
33° 30'
10
15
20
50
150
200
300
400
5
10
15
20
50
150
200
300
a b c d e f g h k l m n o p q r

FIGURE 4

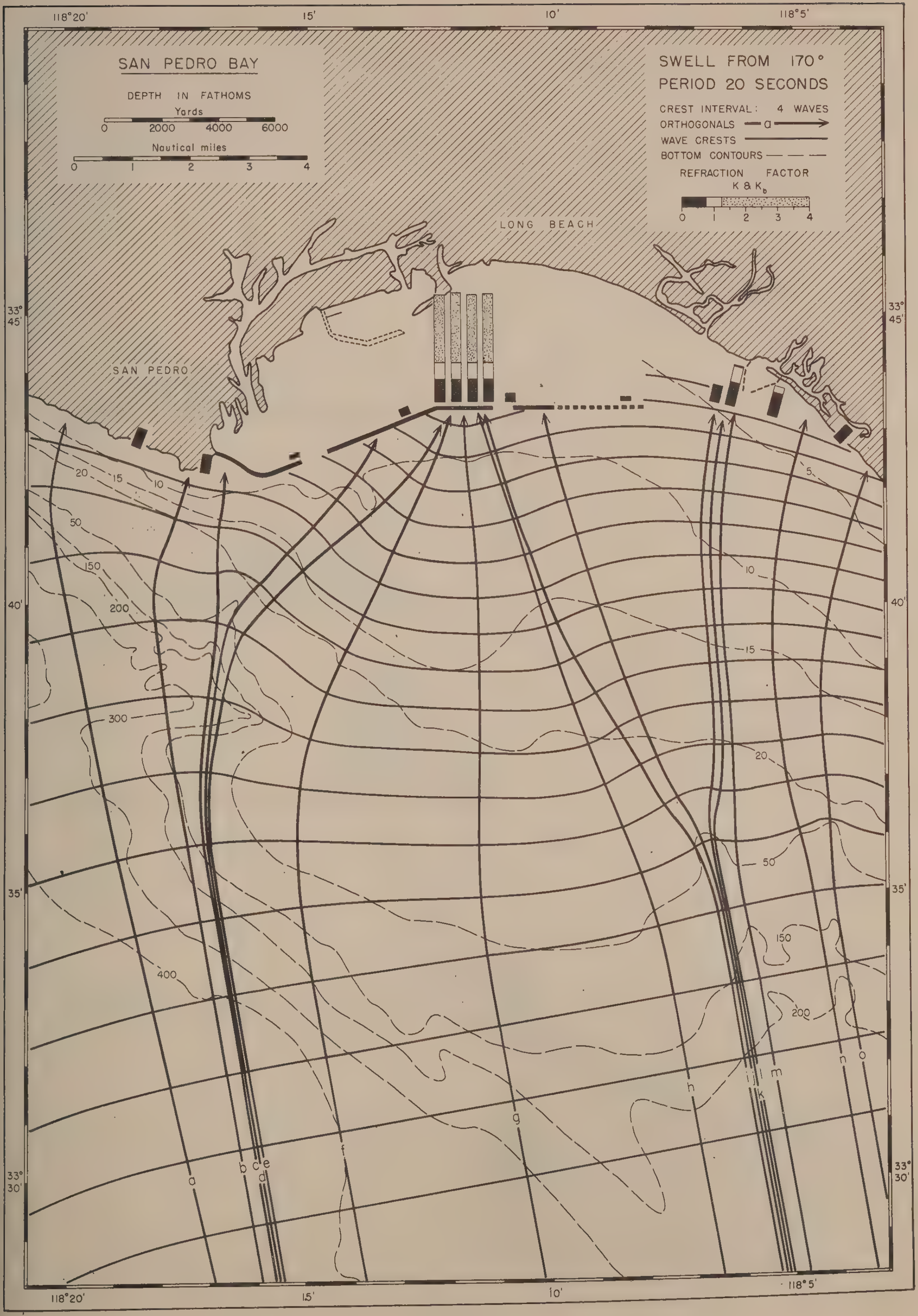

SAN PEDRO BAY
DEPTH IN FATHOMS
Yards
0 2000 4000 6000
Nautical miles
0 1 2 3 4
SWELL FROM 170°
PERIOD 20 SECONDS
CREST INTERVAL: 4 WAVES
ORTHOGONALS a
WAVE CRESTS
BOTTOM CONTOURS
REFRACTION FACTOR
K & K_b
0 1 2 3 4
LONG BEACH
SAN PEDRO
118°20'
15'
10'
118°5'
33° 45'
40'
35'
33° 30'
20
15
10
5
50
150
200
300
400
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o

FIGURE 5

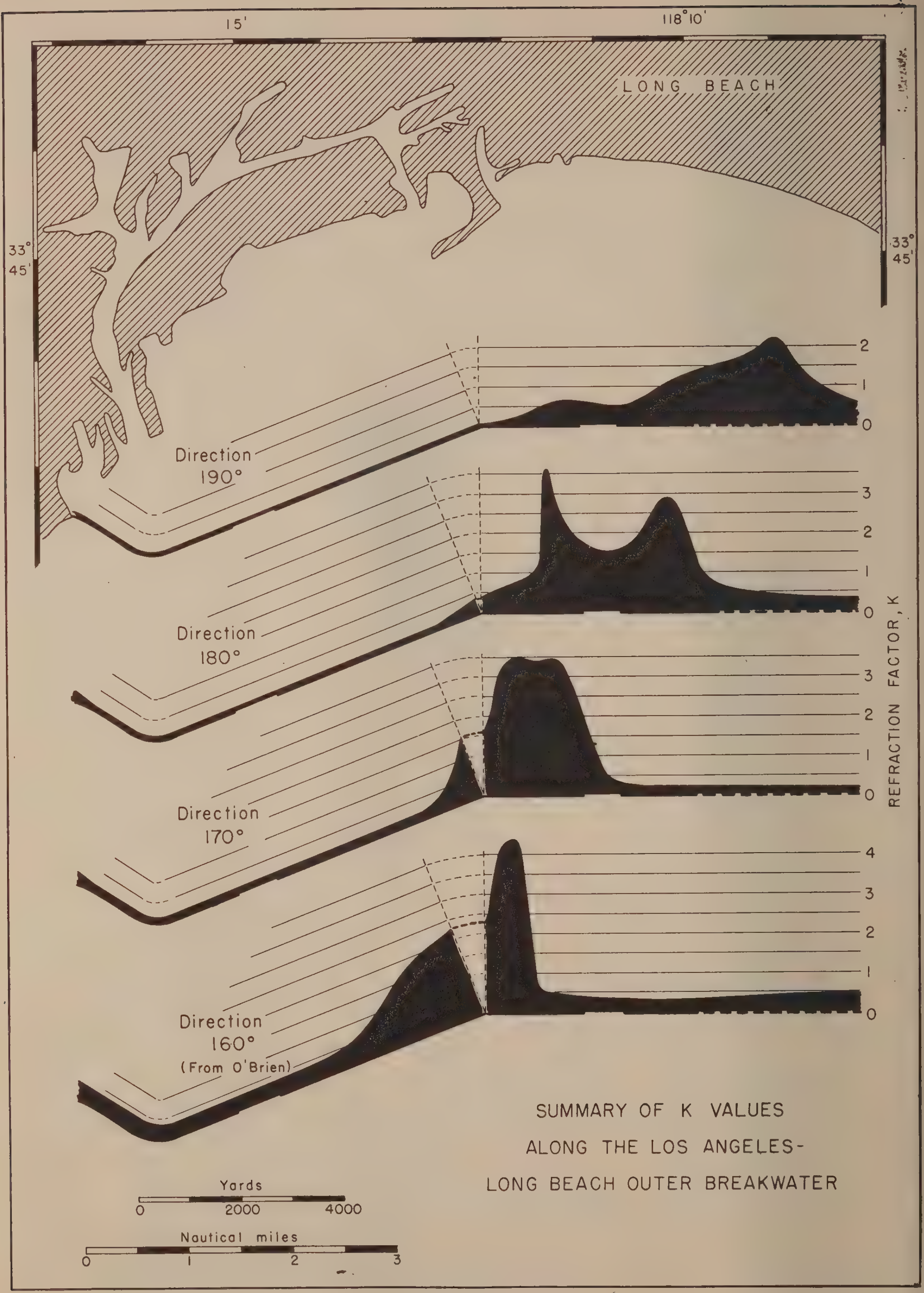

15'
118°10'
LONG BEACH
33°
45'
33°
45'
Direction
190°
Direction
180°
Direction
170°
Direction
160°
(From O'Brien)
REFRACTION FACTOR, K
0
1
2
3
4
SUMMARY OF K VALUES
ALONG THE LOS ANGELES-
LONG BEACH OUTER BREAKWATER
Yards
0
2000
4000
Nautical miles
0
1
2
3

FIGURE 6

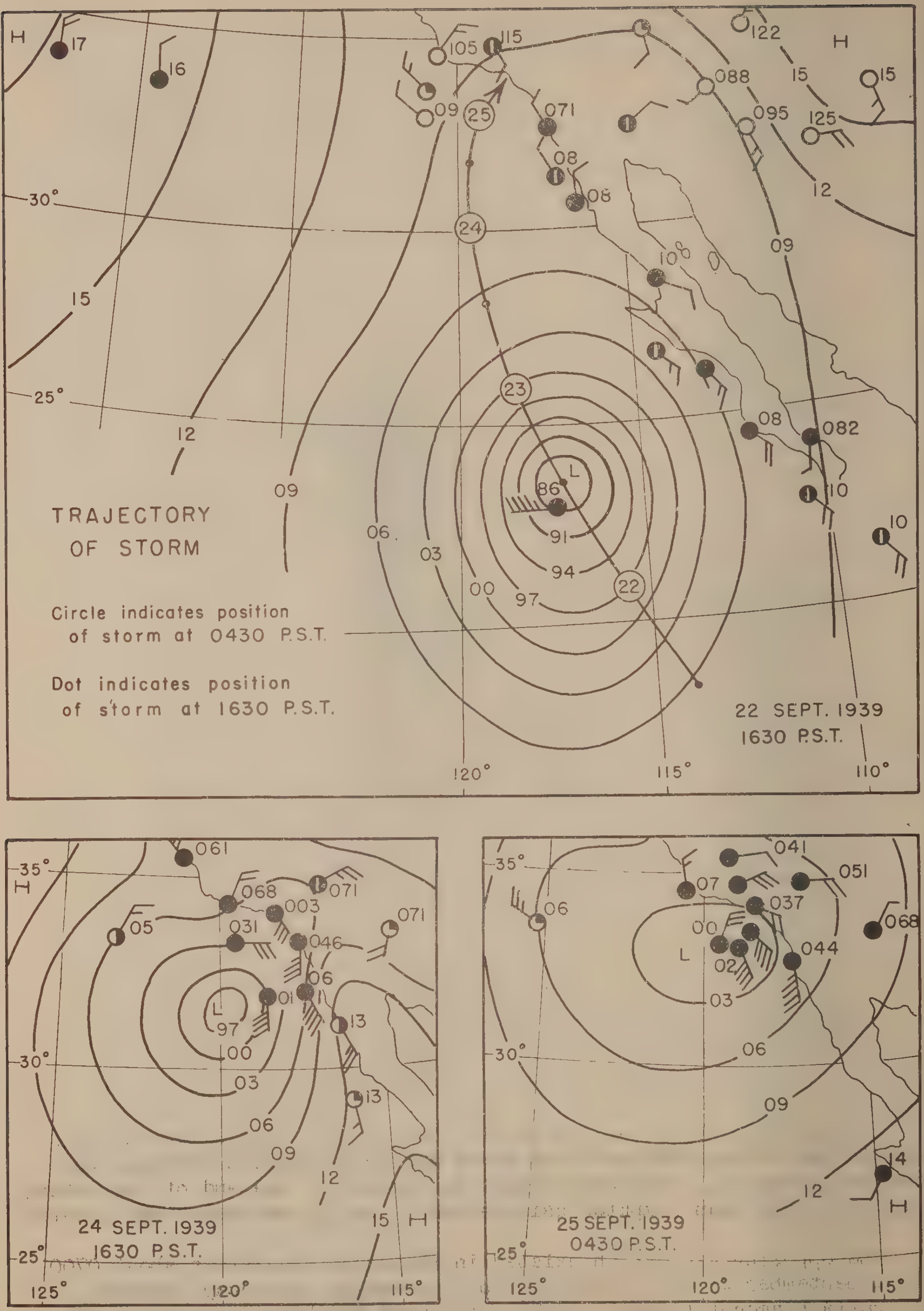
Lower California coast, and it subsequently dissipated after it encountered the coast of Southern California. The weather maps in Figure 7 show that the storm decreased in intensity from September 22 to September 25. As it traveled northward toward the coastline the winds in the eastern portion of the storm were always directed toward Long Beach. This condition, together with the movement of the storm, produced an effective fetch which exceeded 1,000 miles. The velocity of the storm's center was approximately 15 knots during the interval 1630 P.S.T., September 21 to 1630 P.S.T., September 22, after which it gradually decreased to about 6 knots by 1630 P.S.T., September 24.

In order to determine the longest possible effective fetch, within the limits of available weather data, the speed of the wave energy front which remained under the influence of strong winds for the longest time was computed relative to the speed of the storm. This energy front would be expected to emerge from the fetch before the strong winds from the storm reached San Pedro Bay. However, because the wind field quickly elongated and was extended to Long Beach during the period 0430-1630 P.S.T. September 24 as shown in Figure 7, the waves comprising the energy front continued to grow under these winds all the way to Long Beach. In addition, the extended wind field represented an earlier local fetch which produced short period wind waves of considerable height.

Between 1630 P.S.T., September 24 and 0430 P.S.T., September 25, the storm elongated in an east-west direction. Soon after the 0430 map the winds at San Pedro Bay subsided to calm or light and variable, and the storm center moved toward the coast in the region between San Pedro and San Diego. At about 0700 the winds at San Pedro backed to the northeast, but a small fetch still existed to the south. The existeance of this fetch is verified by the south winds which were recorded at San Pedro for some period after the windshift occurred at San Pedro (Table 1). By 1630 P.S.T., September 25 the storm's center was no longer distinguishable.

Computed deep water wave conditions. - The computed deep water characteristics at San Pedro Bay for waves from the tropical storm are tabulated in Table 2 and presented graphically in Figure 8. Swells from westerly directions preceding and following the waves from the tropical storm are also shown on the graph. The time when generation began as shown in Table 2 was the initial time at which the average wind velocity, $\underline{U}$, applied. Prior to this time lighter winds which preceded the main fetch had produced low waves of short period. These waves were still present in the fetch area at the time generation began. As a result, the actual fetch, $\underline{F}$, shown on the weather maps was effectively increased by the distance required to generate the short low waves at velocity, $\underline{U}$. This distance together with the fetch shown on the weather maps and the distance the storm moved with the waves during generation comprise the effective fetch, F_e. The wave height and period at the end of the fetch, $\underline{H_F}$ and $\underline{T_F}$, have been computed using either $\underline{F}$ or $\underline{F_e}$, whichever was greater.

The opposing wind which existed in the decay area after about 0700 P.S.T. September 25 was allowed for by increasing the decay distance, $\underline{D}$, by a certain amount (Arthur, 1948). The wave height and period at the



TRAJECTORY OF STORM

Circle indicates position of storm at 0430 P.S.T.

Dot indicates position of storm at 1630 P.S.T.

22 SEPT. 1939
1630 P.S.T.

24 SEPT. 1939
1630 P.S.T.

25 SEPT. 1939
0430 P.S.T.

H
17
16
105
115
122
H
088
15
15
09
25
071
095
125
08
08
12
30°
24
09
108
15
23
25°
08
082
12
L
86
09
10
06
91
10
03
94
00
97
22
120°
115°
110°
35°
H
061
068
071
003
05
031
071
046
06
L
01
97
13
00
30°
03
13
06
09
12
15
H
25°
125°
120°
115°
35°
041
051
07
06
037
068
00
L
02
044
03
06
30°
09
14
12
H
25°
125°
120°
115°

FIGURE 7

TABLE 1

Hourly Winds for Coastal Stations in Southern California during the Tropical Storm of September 1939

			LOS ANGELES AREA	
	SAN DIEGO		LOS ANGELES**	SAN PEDRO
Date and Time	Direction	Velocity in MPH	Direction	Velocity in MPH
24-0900*	S	7	SE	3
1000	S	12	SE	3
1100	SE	24	SE	9
1200	S	29	SE	21
1300	S	29	SE	30
1400	SE	30	SE	30
1500	SE	25	SE	40
1600	SE	27	SE	42
1700	SE	26	SE	36
1800	SE	25	SE	34
1900	SE	24	SE	40
2000	SE	24	SE	37
2100	SE	25	ESE	39
2200	SE	24	ESE	39
2300	SE	24	ESE	35
25-0000	SE	24	ESE	32
0100	SE	22	ESE	40
0200	SE	24	ESE	38
0300	SE	24	ESE	41
0400	SE	29	ESE	43
0500	SE	27	ESE	41
0600	S	29	ESE	34
0700	S	24	NE	26
0800	S	22	NE	16
0900	S	21	NW	12
1000	S	19	NW	15
1100	S	18	W	18
1200	S	15	W	24
1300	S	15	W	22
1400	S	15		
1500	S	13		

* September 24, 1939, 0900 Pacific Standard Time.

** Wind directions were not recorded at San Pedro.

TABLE 2. - Computations of Deep Water Wave Conditions for San Pedro Bay during Tropical Storm of September, 1939

Time and date generation began at wind velocity, U	0930 9-24	1000 9-24	1030 9-24	1100 9-24	1130 9-24	1130 9-21	2000 9-21	0700 9-22	1730 9-22	0430 9-23	1030 9-23	1630 9-23	2230 9-23	0430 9-24	1030 9-24	1630 9-24	2230 9-24	0430 9-25	Small waves existing in rear portion of fetch	
Average wind velocity, U (knots)	15	20	30	35	37	36	36	36	36	36	36	36	36+	36+	37-	37	38	39		
Fetch, F (naut. miles)	165	165	160	155	150	200	200	200	200	195	190	185	170	165	165	145	85	35		
Effective fetch, F_e (naut. miles)						1250	1100	950	800	660	570	500	405	325	250	185	120	55		
Duration of wind, t_d (hours)	1	2½	3	4½	8	Greater than 83														
Minimum duration, t_{min} (hours)	28	24½	20	18	17	83	75	67	59	51	46	42	36½	31	25½	20	14	8		
Wave height at end of fetch, H_F (feet)	2.0	3.4	6.5	10.4	16.8	28.5	28.2	27.9	27.6	27.3	26.9	26.7	26.4	26.0	25.0	24.0	23.0	18.0	9.0	4.5
Wave period at end of fetch, T_F (seconds)	2.0	2.5	3.6	4.6	5.9	14.0	13.4	12.7	12.4	11.7	11.3	10.8	10.3	9.8	9.2	8.4	7.5	6.1	4.6	4.0
Time when waves leave fetch and enter decay area											0530 9-25	0730 9-25	0800 9-25	0830 9-25	0900 9-25	0930 9-25	0930 9-25	0930 9-25	1230 9-25	1430 9-25
Decay distance, D (naut. miles)											15	20	30	45	60	70	70	70	70	70
Wind velocity in decay area,* U' (knots)												-18	-18	-18	-18	-18	-20	-20	-15	-12
Effective decay dist., D_e (naut. miles)												31	47	72	98	118	130	142	137	134
Height at end of decay area, H_D (feet)											26.8	25.8	24.8	23.4	21.2	19.0	17.0	11.5	4.5	2.0
Period at end of decay area, T_D (seconds)											11.3	10.9	10.5	10.1	9.8	9.2	8.5	7.3	6.0	5.5
Travel time to end of decay area, t_D (hours)											1	1¼	2	3	4	5¼	5 3/4	8	8 3/4	10
Computed arrival time	1030 9-24	1130 9-24	1230 9-24	1330 9-24	1530 9-24	1730 9-24	2000 9-24	2300 9-24	0130 9-25	0430 9-25	0630 9-25	0845 9-25	1000 9-25	1130 9-25	1300 9-25	1445 9-25	1515 9-25	1730 9-25	2115 9-25	0030 9-26

*Negative sign indicates direction of wind was opposite direction of wave movement

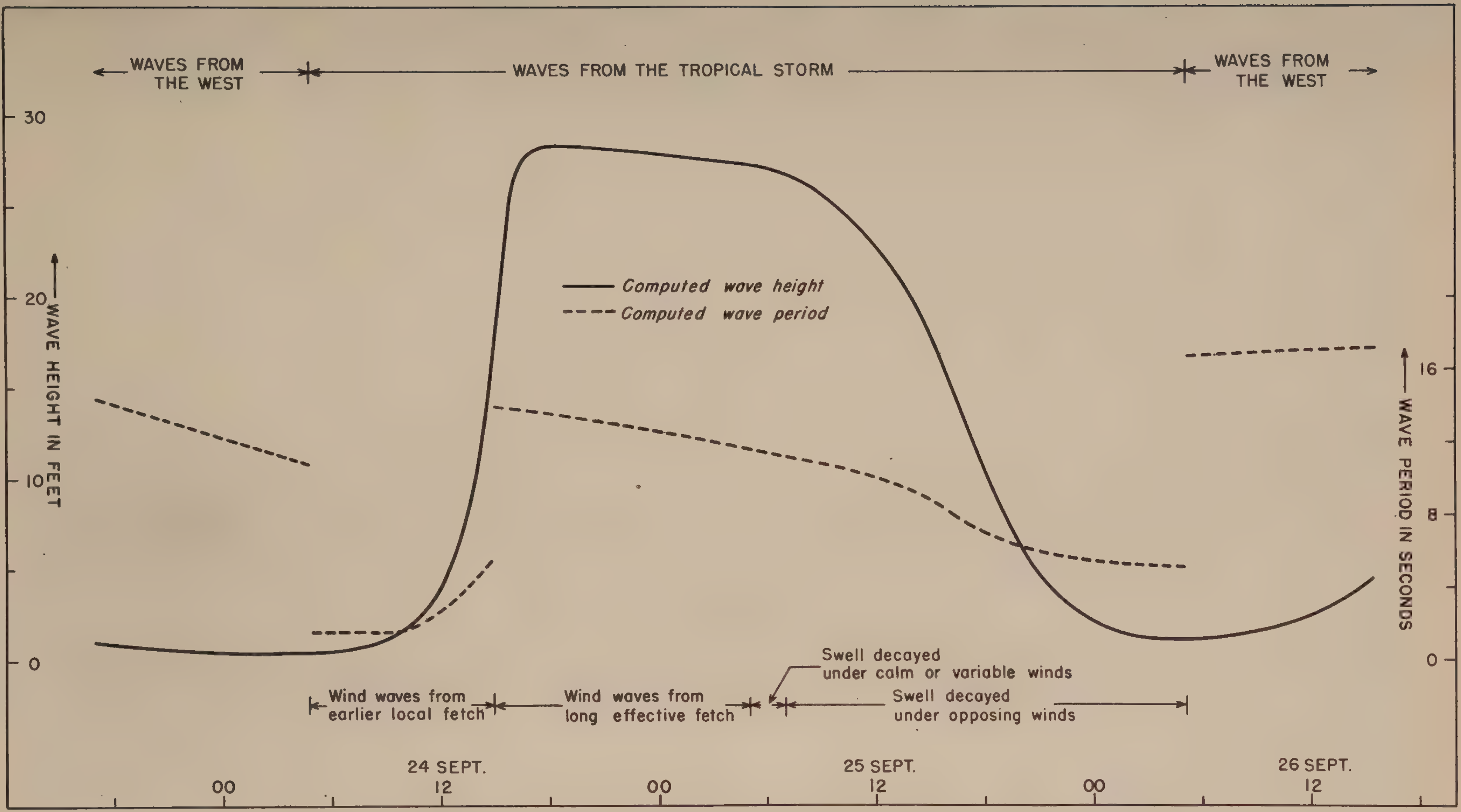


FIGURE 8 - COMPUTED DEEP WATER WAVE CONDITIONS AT SAN PEDRO BAY

end of the decay area, H_D and T_D , which are shown in Table 2, have been computed using the effective decay distance, D_e, where applicable. In the computations no diffraction correction (Francis, 1944) has been applied because (1) no decay distance existed until after 0430 P.S.T., September 25 and (2) after this time the fetch no longer resembled the circular fetch characteristic of a tropical storm.

The waves from the tropical storm may be divided into four parts as shown in the lower part of Figure 8. The short period wind waves from the earlier local fetch increased rapidly in height at about 1200 P.S.T., September 24 and remained predominant until about 1430 P.S.T., September 24. At that time waves from the long effective fetch arrived. These had not traveled through decay areas and were still growing under the influence of strong winds when arriving at San Pedro Bay. They were of great height and relatively long period. The rapid build-up in wave height shown in Figure 8 would have been even more accentuated if the earlier local fetch had not developed. Such a quick build-up of wave height is a characteristic common to waves from tropical storms, and it has been reported for certain other tropical storms that strong winds and very high waves arrived simultaneously. Soon after the arrival of waves from the long effective fetch the computed wave height was greater than 28 feet and the corresponding period 14 seconds. For almost 12 hours these waves maintained great height, but their period steadily decreased with time.

The waves shown between 0500 and 0700 September 25 represent swell from the small fetch to the south decayed under calm or variable winds. After 0700 when the winds at San Pedro backed to northeast the waves represented swell decayed under opposing winds, and the height and period decrease fairly rapidly. Not until about 0500 September 26 did the swell from the west become larger than the swell from the weak residual fetch located to the south.

Refraction pattern and distributing of damage. - As indicated by the geographical locations of the tropical storm's wind field shown in Figure 7 the wind waves and swell from this storm approached Long Beach from directions varying between 150° and 190° in deep water. Figure 9 is a portion of the refraction diagram for 175° and 14 seconds period. This corresponds to the period of the highest waves from the long effective fetch reaching San Pedro Bay. The complete diagram from which Figure 9 is taken is shown in the inset and was drawn with a crest interval of 2 waves on a detailed chart of the bottom topography. The refraction factors are presented in the same manner as on the diagrams for southern hemisphere swell.

The damaged portions of the Los Angeles-Long Beach Detached Breakwater and the intensity of the damage within these areas are also shown in Figure 9. It is evident that the amount of damage was increasingly great from west to east along this breakwater while the Long Beach breakwater escaped without damage. From this it appears that the wave forces were considerably greater near the easterly end of the detached breakwater. Because of its seaward location, the detached breakwater apparently provided shelter for the undamaged Long Beach Breakwater.

175° was about the most easterly direction from which waves could have produced the observed damage pattern. From more easterly directions the waves probably would have resulted in damage to the Long Beach Breakwater. Consequently, it appears that the damaging waves approached San Pedro Bay from directions within the narrow sector from 175° to about 185°. For directions west of 185° the effect of refraction around Catalina Island considerably reduced the wave force on the breakwater.

Figure 9 shows that the refraction factors increase progressively toward the east end of the detached breakwater from 0.37 between orthogonals a and b to 1.65 between orthogonals f and g with corresponding heights varying from 10 to about 45 feet, disregarding interference between wave trains.

Unfortunately, actual measurements of wave height and period at San Pedro Bay during this storm were not made[2], but the direction of wave approach was observed by means of a transit from Pt. Fermin near the westerly end of San Pedro Breakwater. This observation indicated that waves came from the southwest concurrently with waves from the southeast, and that the southwest waves appeared to be the larger. Although, it is impossible to determine without observations of wave period whether or not one train of waves was southern swell arriving simultaneously with the waves from the tropical storm, the observed directions of wave approach and distribution of damage can be fully explained by the tropical storm waves alone.

Since waves from a tropical storm are propagated radially from the storm's center, there is a certain amount of variability in direction from which the waves may come. The higher waves arriving at San Pedro Bay were probably generated near the center of the storm, but at the same time some waves were being generated by the weaker winds nearer the east side of the storm just off the coast, and these smaller waves approached Long Beach from directions which were more to the southeast. Having less height and shorter periods they experienced little refraction in crossing San Pedro Shelf and reached the breakwater retaining their original direction. On the other hand, the large waves from the long effective fetch approaching from directions between 175° and 185° were refracted most over San Pedro Sea Valley so that the wave crests in the vicinity of the breakwater were oriented in such a way that the waves appeared to come from directions more twoard the southeast.

Summary and Conclusions

The characteristics of waves destructive to the harbor breakwaters in the Long Beach-San Pedro area have been examined. As a result of refraction over the complicated bottom topography in San Pedro Bay this wave energy was concentrated at certain parts of the breakwaters. The refraction effect of the bottom topography upon waves from the tropical storm was similar to that for southern hemisphere swell but less pronounced because the tropical storm waves had shorter periods.

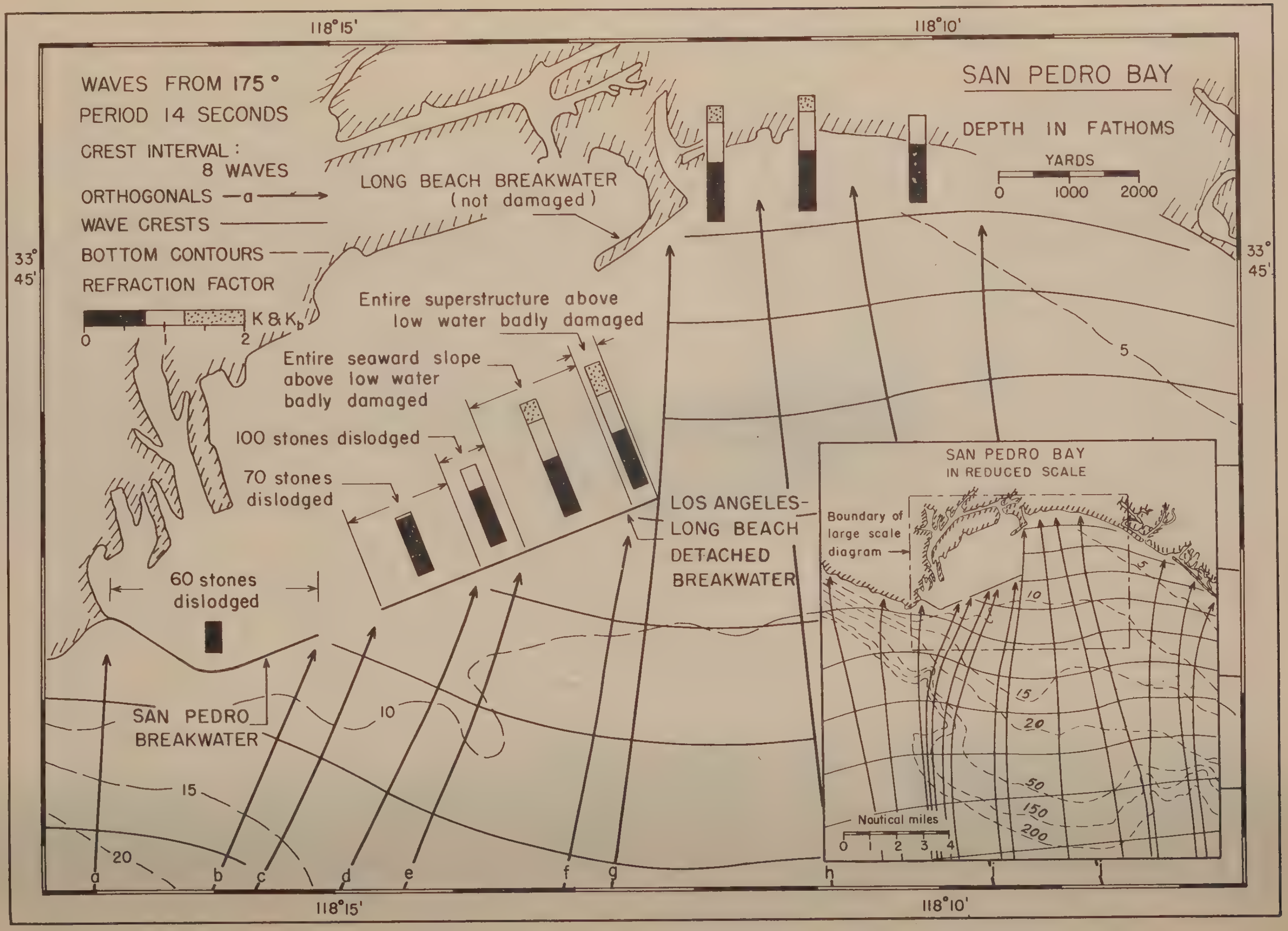

118°15'
118°10'
33° 45'
SAN PEDRO BAY
DEPTH IN FATHOMS
YARDS
0
1000
2000
WAVES FROM 175°
PERIOD 14 SECONDS
CREST INTERVAL: 8 WAVES
ORTHOGONALS —a→
WAVE CRESTS
BOTTOM CONTOURS
REFRACTION FACTOR
K & K_b
0
1
2
LONG BEACH BREAKWATER (not damaged)
Entire superstructure above low water badly damaged
Entire seaward slope above low water badly damaged
100 stones dislodged
70 stones dislodged
60 stones dislodged
LOS ANGELES-LONG BEACH DETACHED BREAKWATER
SAN PEDRO BREAKWATER
5
10
15
20
a
b
c
d
e
f
g
h
i
j
SAN PEDRO BAY IN REDUCED SCALE
Boundary of large scale diagram
Nautical miles
0
1
2
3
4
5
10
15
20
50
150
200

FIGURE 9

The predominant characteristics common to all the preceding refraction diagrams can be attributed to specific features of the bottom topography. In each case a zone of divergence is produced by the sea valleys located on either side of the San Pedro Shelf. And, these valleys aid in producing greater convergence over the extended shelf lying between them. Slight changes in wave direction result in sizeable displacement of the zones of convergence and divergence, while the effect of wave direction upon the magnitude of the refraction factor is somewhat less marked. Because of interference between wave trains, the largest waves at certain parts of the breakwater may contain greater intensity of energy than the amount indicated by the refraction factors.

The computed wave height and direction of approach of the tropical storm waves agree with observed conditions. Without additional observations of both wave height and period, it is impossible to test the accuracy of the existing technique for estimating waves from a tropical storm. The computations indicate that waves at Long Beach from such a tropical storm contain far greater energy than wind waves or swell from other northern hemisphere storms which pass to the south of Long Beach. However, because of the rarity of occurrence of tropical storms which can produce damaging waves in the Long Beach region it may be more economical and practical to plan to repair the existing breakwaters after each of these storms than to build the breakwaters heavy enough to withstand such wave attack.

Acknowledgements

The U. S. Weather Bureau, Department of Commerce, and the California Institute of Technology have furnished the meteorological data needed for this study. Mr. R. O. Eaton, Corps of Engineers, has provided information pertaining to wave observations and damage to harbor structures in the Long Beach-San Pedro area.

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Footnotes

1 Measurements of wave height were made by Mr. R. O. Eaton, Corps of Engineers and communicated by letter to Dr. Walter H. Munk of Scripps Institution of Oceanography. Wave heights of 15 and 18 feet were recorded in depths of 37 and 27 feet, respectively.

2 Lieut. H. F. Nowak, U.S.N., has recently given a verbal description of the height of the wave crests as he observed it from aboard the aircraft carrier Lexington on September 24, 1939. The Lexington was at anchor in water between 50 and 60 feet deep east-northeast of the eastern end of the detached breakwater. Lieut. Nowak estimated the tops of the wave crests to be about 24 feet above mean water level. If it is assumed that the trough of the waves is one-fourth of the wave height below the mean water level the total wave height is 32 feet. The computed wave height in this area, allowing for refraction and depth, is between 32 and 39 feet, depending upon the exact position for which the refraction factor is computed.

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Contribution No. 476

Correlation Between Temperature of Water and Size of Marine Fishes on the Atlantic and Gulf Coasts of the United States

By Gordon Gunter

Reprinted from Copeia, 1950, No. 4, December 22

Correlation Between Temperature of Water and Size of Marine Fishes on the Atlantic and Gulf Coasts of the United States[1]

By Gordon Gunter

ABOUT seventy years ago Karl Möbius noted that several species of invertebrates from the Arctic seas near Greenland grew to larger size than they did in the Baltic Sea (Semper, 1881: 132). It is now well recognized that animals in polar seas grow to larger size than the same species in temperate or tropical seas. One of the most recent statements is that of Mann (1948), who reported "giant size of invertebrates" as one of the characteristics of Antarctic life. Many naturalists have noted the phenomenon. Several references may be found in the general texts by Murray and Hjort (1912: 612), Hesse, Allee and Schmidt (1937: 159), and Sverdrup, Johnson and Fleming (1946). Kofoid (1930) and others have shown that certain protozoans and other organisms in cold currents grow larger than those in warmer waters nearby. Tropical copepods are smaller than polar species (Sverdrup, *et al.*, *op. cit.*). Warming (1909) has noted that in colder seas the brown algae are larger. The same law holds for most marine organisms. Probably Weymouth and his colleagues have given the most precise data on this subject. In a study of the growth of the Pacific cockle (*Cardium corbis*

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[1] Contribution No. 476 of the Scripps Institution of Oceanography of the University of California.

Martyn), Weymouth and Thompson (1931) showed that the northern forms, in contrast to the southern, have a slower initial but more sustained growth, and reach greater age and larger size. Weymouth, McMillin and Rich (1931) showed that in the razor clam (*Siliqua patula*), growth in southern localities as compared with the northern is initially more rapid but less sustained, leads to smaller size, and is associated with shorter life span.

It is also known that northern species are larger on the whole than more southerly species of the same genus. The directions are of course reversed in the southern hemisphere. Wimpenny (1941) reviewed much of the literature on this subject and discussed some of the exceptions to the general rule.

Delayed sexual maturity, longer life, slower growth and greater final size are characteristics of animals in colder seas. The phenomenon seems to be dependent upon progressive retardation of growth by lowering temperatures poleward. It is well known that sexual maturity and growth are hastened by high temperatures, but that certain growth inhibitors operate at the time of sexual maturity to slow or stop growth. Therefore, the faster the growth, the less the final size. There is also a direct correspondence between the rate and final degree of differentiation of certain gross morphological features and the growth rate. Hubbs (1926) reviewed the literature as it applied to fishes. Information on other animals is scanty.

Differences in size, correlated with temperature, were usually thought of as occurring among wide-ranging species in the seas. The purpose of this paper is to call attention to size-temperature relationships among fishes of the United States east coast. The differences in this respect between fishes of the Gulf Coast and those of the Middle Atlantic states have an effect upon the commercial fisheries and upon the life histories of the species concerned in the two regions.

Discussion

Several species of fishes extend from the western Gulf of Mexico around the Florida Peninsula to Long Island, thus covering a coastline of about 3,000 miles and a north to south direction of 1500 miles. Some extend into the West Indies and beyond. Greater size of these fishes along the Middle Atlantic states as compared to those in Gulf waters is shown by several facts. Several fishes utilized commercially in New Jersey, Virginia and other Atlantic states are never thought of as anything but trash fish along the Gulf Coast. The chief ones are the harvestfish (*Peprilus paru*), the butterfish (*Poronotus triacanthus*), the spadefish (*Chaetodipterus faber*), the spot or flat croaker (*Leiostomus xanthurus*), and the croaker (*Micropogon undulatus*). The first 3 species have never been taken commercially along the Gulf Coast. After several years acquaintance with *C. faber,* I learned with considerable surprise that a size of 10 to 12 pounds is not uncommon for this species in Chesapeake Bay (Hildebrand and Schroeder, 1927). The amount of commercial production of these species for several of the Atlantic states can be seen in any of the annual statistical reports of the U.S. Fish and Wildlife Service. The production of the first 3 is small. In 1934, a year picked at random, according to federal statistics (Fielder, 1936), the Atlantic states produced 7,443,250 pounds of spots while the Gulf states produced 13,800 pounds. Nevertheless, this fish is very common on the Gulf Coast and may be among the upper 10 in species mass (see Gunter, 1945: tables 60–65). Pearson (1929) concluded that on the Texas Coast most of these fish died after the first spawning, and my data (Gunter, *op. cit.*) corroborated that view. First spawners are probably in year-class II. Among 1,264 fish, from Gulf waters, I took only 15 above 255 mm. in length. Most spots simply do not attain commercial size on the Gulf Coast.

The croaker deserves special mention. In Virginia this fish grows to a size of 4 to 5 pounds and the fishery for it may amount to over 40,000,000 pounds a year. In Texas they seldom attain an important size, and evidence has been presented (Gunter, *op. cit.*) that usually they die at the end of two years at a length of about 250 mm. Thus, in spite of the fact that the croaker is one of the most abundant of all fishes and is certainly among the upper 4 in species mass in this area (Gunter, *op. cit.*), few fish grow to market size. According to Fiedler (1936), in 1933 the Gulf states produced 683,300 pounds of croakers and the Atlantic states produced 31,812,050 pounds. In the federal statistics for 1938 (Fiedler, 1940), the same areas were credited with a production of 202,200 pounds and 64,763,000 pounds, respectively. Every few years on the Texas Coast, at irregular intervals not well known, there are runs of croakers that weigh from 2 to 4 pounds. They are distinguished by the name "golden croakers." They are, however, the same fish and are comparable in size and weight to the Virginia fish. They are not to be confused with the West Indian croaker (*Micropogon furnieri*), which has been reported from the southern tip of Texas. Why certain year-classes attain greater size than others is unknown. Possibly some large croakers are present every year, but are not numerous enough to be of particular note in the commercial fishery. Weymouth (1918) has shown that on the Pacific Coast of this country animals attain a larger size when the growing (warm) season is longer. Presumably on the Gulf Coast the situation would be reversed and larger size would be correlated with colder years and retardation of the rate of growth. Years with colder extremes do occur (Gunter, 1948), but there is no evidence that they are correlated with the larger croakers. Furthermore, such fish probably take 4 or 5 years to reach maturity. Possibly they abandon the warm, shallow bays for the colder waters of the Gulf and grow up there, and do not follow the usual life cycle. In any case it is known that large croakers, similar to the "hardheads" of Virginia, appear occasionally along the Texas Coast.

It is well established that the redfish (*Sciaenops ocellata*) on the Texas Coast does not spawn until a length of 32 inches is reached (Pearson, 1929). However, during the past 5 years 3 redfish, with roe at smaller sizes, from the south Texas Coast have been brought to my attention. All were taken within 100 miles of Mexico. Two were 17 and one was 16 inches in length. Inquiry among fishermen who work down the Mexican Coast has brought the information that similar, small, sexually mature redfish are not uncommon south of the Rio Grande, but are very rare north of it. At my request, Mr. C. E. Dawson, Jr., of the University of Miami Marine Laboratory, has made some inquiry among the fishermen of the southern part of the west Florida Coast. They state that the smallest redfish with roe there are about 12 inches long, but that the average minimum length is 15 inches. Small redfish with roe on the south Texas, Mexican, and southern Florida coasts correspond to what we would expect from rising temperatures southward in those regions. So far as is known no redfish of the northern Gulf Coast become sexually mature at less than 32 inches in length.

Great numbers of large croakers are produced in Chesapeake Bay, while on the Gulf Coast the lives of the fish are foreshortened and large ones are very much in the minority. The same holds true of the spot. Nevertheless, one of the most striking things about the fish populations of the shallow Gulf waters is the predominance of the family Sciaenidae, led by the croaker, as I have shown in several papers (summarized in Gunter, 1945). The contrast of the two abundant croaker populations —that of the Middle Atlantic states which supports a large fishery, and that of the Gulf states which supports none of consequence—raises interesting fishery and ecological questions.

TABLE I

A LIST OF FISHES FROM CHESAPEAKE BAY AND THE TEXAS COAST WITH MAXIMUM SIZES IN MILLIMETERS RECORDED BY HILDEBRAND AND SCHROEDER (1927) AND BY GUNTER (1945).

Only those species for which the authors recorded 10 or more specimens are listed

Species	Chesapeake Bay		Texas	
	Size	Number	Size	Number
Anchoa mitchilli	97	many	95	11,054
A. hepsetus	152	many	141	1,283
Dorosoma cepedianum	330	31	280	692
Cyprinodon variegatus	76	many	93	6,673
Lucania parva	58	many	53	476
Membras vagrans	115	numerous	98	710
Mugil cephalus	381	many	356	4,940
Mugil curema	150	many	303	619
Trachinotus carolinus	200	24	185	556
Caranx hippos	195	15	285	34
Poronotus triacanthus	235	many	200	47
Orthopristis chrysopterus	285	many	227	290
Lagodon rhomboides	185	many	225	907
Archosargus probatocephalus	15 lbs.	many seen	405	25
Archosargus probatocephalus	(30 lbs.)	(observed)	—	—
Micropogon undulatus	508	numerous	370	15,847
Pogonias cromis	(40 lbs. seen)	17	460	174
Bairdiella chrysura	225	many	164	236
Leiostomus xanthurus	345	many	282	1,264
Menticirrhus americanus	393	many	318	326
M. littoralis	160	many	340	54
Cynoscion nebulosus	(16 lbs. observed)	many	515	464
Chaetodipterus faber	10 to 12 lbs. not uncommon	13	195	23
Gobiosoma bosc	60	many	52	173
Chilomycterus schoepfi	225	11	273	26
Achirus fasciatus	202	numerous	140	98
Etropus crossotus	115	20	156	210

In contrast, the size and length of life of the redfish (*S. ocellata*) on the Gulf Coast are not foreshortened. Only a few small spawning redfish are found in the Gulf and these are to the south. Also in contrast to the croaker and spot, the chief fishery center is farther south, lying in Florida and Texas, the only two states which produce over a million pounds a year. Spots, croakers and redfish all show the same general response to higher temperatures southward, in a modification of their life cycle; but in the two croakers the feature makes itself apparent at higher latitudes. The range of all 3 species is generally given as Massachusetts to Texas. However, *S. ocellata* is the most southerly fish, and when the southward range of the 3 species is finally known it will doubtless be found that the redfish extends farthest in that direction.

More evidence of a difference in maximum size between Middle Atlantic and Gulf fishes is shown by certain published measurements from the two areas. Hildebrand and Schroeder (1927) recorded some 45 species of fish from Chesapeake Bay which Gunter (1945) also listed from the Texas Coast. In both reports maximum sizes were usually given, but for a few species this size was not given in one paper or the other. For some other species large fish were known or observed from Chesapeake Bay, but were not measured or preserved. All species for which the authors reported 10 or more specimens and gave the maximum sizes are shown in Table I. Therefore, 19 species listed by Hildebrand and Schroeder and by Gunter are omitted from the present discussion because obviously the records are not representative of the species. These include rare strays into the Chesapeake region and some that were rarely caught in one region or the other. Nevertheless, 14 of the rarely caught species are recorded as being larger from Chesapeake Bay. Table I gives the maximum sizes of species for which the authors could or probably were getting more representative samples from the population. These do not necessarily include the very largest fishes residing in the two areas. Hildebrand and Schroeder did not always give the number of specimens in their collections and the numbers taken in the two areas cannot be compared. Nevertheless, it is significant that of 26 comparable species from the two localities, for 18 of them the larger fishes were recorded from Chesapeake Bay. The exceptions were *Cyprinodon variegatus, Mugil curema, Lagodon rhomboides, Menticirrhus littoralis, Caranx hippos, Chilomycterus schoepfi* and *Etropus crossotus*. Larger *L. rhomboides* than those measured are commonly caught in Chesapeake Bay, and in some years a few thousand pounds are marketed.

Lastly, some consideration should be given to the differential effect of temperature on morphogenetic processes. Divergence or differentiation parallels the growth rate, both in rate and degree (Hubbs, 1926). Apparently any growth-retarding factor has the same effect, in this respect, as low temperature. A fast-growing fish may differentiate faster in spines, scales, bony plates, number of vertebrae, body proportions, etc., but differentiation stops sooner than in slow-growing fish; and although at comparable sizes a cold-water animal may be more juvenile in appearance than specimens from warmer waters, in the long run it comes to possess more spines, meristic elements, etc. In other words, in general the final degree of differentiation in a cold-water fish is greater than in warm water congeners, although the rate is slower. Hubbs (*op. cit.*) discussed the few exceptions to this general rule. These facts should be held in mind by taxonomists and students of speciation. Certain constant differences in fishes that are correlated with geographic distribution may be no more than differences produced directly by the temperature of the environment. As such they are not indicators of genetic or hereditary separation at all.

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The Nature of Some Fluorescing Substances Contained in a Deep-Sea Mud [1]

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INTRODUCTION

t was found earlier that some colorless polyenes such as phytofluene or phytofluenol (2) are widely spread in land plants and impart nse fluorescence to their extracts. In view of the fluorescence of mud racts, it seemed advisable to extend our experiments to such mate- s. As is well-known, phytofluene in many cases accompanies caro- oid pigments in the land flora. On the other hand, it was shown by and his collaborators (3) that sediments of the ocean floor contain stantial amounts of carotenoids deposited there centuries ago.

he sample studied in the present work was collected from a water th of 216 m., and the mud depth amounted to 155–160 cm. The lyzed mud would range in age from fresh material (at the top) to e 960 years at the lowest level of the core (3).

hromatographic resolution of our extracts confirmed the statement ox, Updegraff, and Novelli (3) that in deep-sea muds the hydro- on carotenoids by far exceed the oxygenated pigment types. In sample described below, almost no xanthophylls were present. ong the eight or nine pigments, β-carotene was the relatively major . Remarkable was the presence of a particularly strongly adsorbed red nent possessing its main extinction maximum in hexane at 481 mμ. contrast, neither phytofluene nor similar colorless, fluorescing enes could be detected. The moderately intense, bluish gray fluores-

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cence of the extracts was mainly caused by compounds of non-poly type whose spectral curves appear in Fig. 1. Since the stability of ph fluene *in vitro* is far inferior to that of polyenes possessing a subs tially longer conjugated system, phytofluene possibly is the first t destroyed under the conditions which prevail in deep-sea muds.

EXPERIMENTAL

The mud cores (3 and 4) were obtained off the coast of Sout California at the respective locations: lat. 32°37.84′ N, long. 1 22.18′ W; and lat. 32°37.72′ N, long. 117°22.10′ W. Mud from the 35–40 cm. of a core yielded the analytical data listed in Table I wh are based upon samples dried for 48 hr. at 100°C. under reduced p sure, giving a water-loss of about 55%.

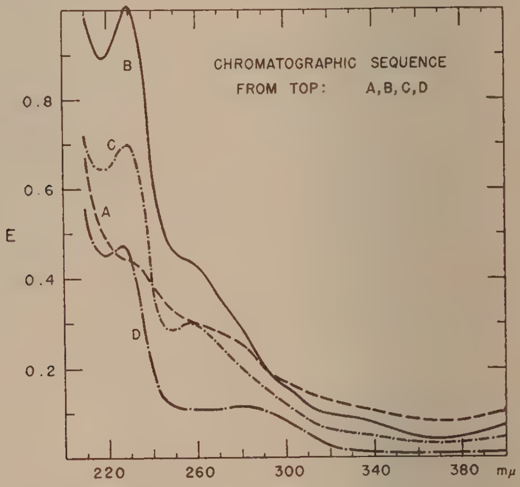

FIG. 1. Spectral curves (in hexane) of some fluorescing compounds containe in a deep-sea mud sample; *E* designates optical density.

A 15-kg. sample (wet) was stirred with methanol and upon sedin tation the supernatant liquid was siphoned off. After we had repe these operations, the combined solutions were extracted thorou with petroleum ether (b. p. 60–70°). The remaining material was tracted four times with petroleum ether–methanol mixtures (1:1, 3:1, and 3:1). After filtration in a basket centrifuge (diameter, 20 c

TABLE I

Analytical Data For Some Organic Constituents of a Dried Deep-Sea Mud Sample[a]

	%
otal organic matter (by chromic acid oxidation; ferrous ion was absent and sulfide negligible)	5.46
otal organic nitrogen (Kjeldahl)	0.32
otal lipide-soluble matter (by extraction with ethanol–ether 1:1) 0.145% (or 2.65% of total organic matter)	
Nonsaponifiable matter 0.066% (or 45.6% of lipide-soluble matter; soluble in petroleum ether)	
Organic acids 0.055% (or 37.9% of lipide-soluble matter; soluble in petroleum ether)	
Residue 0.024% (or 16.6% of lipide-soluble matter; insoluble in petroleum ether)	

[a] These analyses were carried out by Mr. E. F. Corcoran under the direction of one the authors (D. L. F.).

e solutes were transferred into petroleum ether by the addition of ater. The extracts were then washed once with water, dried over dium sulfate, concentrated *in vacuo* to 1 l. and kept over a layer of % methanolic KOH for a night. After the elimination of the alkali washings, the dried, orange-brown solution was concentrated to 150 l. and developed on a calcium hydroxide–celite column (3:1; 28 × 7.5 n.) with petroleum ether containing 2% acetone. In the following chroatogram the figures denote the height of zones, in millimeters:

2 two red streaks
2 light pink: fluorescing compound *A*
11 several minor pigment zones
17 empty interzone
10 pale orange
10 empty interzone
13 orange: β-carotene (relatively main pigment)
2 colorless (overlapping with pigments): fluorescing compound *B*
10 very pale orange
10 almost colorless: fluorescing compound *C*
50 pale yellow
115 colorless
Filtrate: fluorescing compound *D*.

By systematic fractionation and repeated re-chromatographing which ill not be described in detail, the compounds *A*, *B*, *C*, and *D* were obtained in almost colorless, and chromatographically homogeneous solutions. Figure 1 is based on light absorption measurements taken o a Beckman spectrophotometer.

SUMMARY

A deep-sea mud sample (age up to 960 years) was found to be free o phytofluene or other colorless polyenes, although epiphasic caroteno pigments such as β-carotene [cf. (3)] were present. The observed fluor escence of the extracts was caused mainly by four non-polyenic com pounds (Fig. 1).

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Contribution No. 478

REALITY AND ILLUSION IN OCEANOGRAPHIC SURVEYS[1]

By

ALBERT DEFANT[2]

ABSTRACT

Care must be exercised in selecting time intervals and spacings between stations along oceanographic profiles in order to avoid erroneous conclusions regarding the mean circulation. By proper combinations of time intervals and spacings, the effect of internal waves of tidal periods, which are the source of these errors, can be suppressed. The application of these principles to the Marine Life Research cruises of the Scripps Institution is discussed.

INTRODUCTION

Generally oceanographic surveys are made by one or several ships occupying a series of oceanographic stations along specific profiles according to a predetermined plan. To obtain the best possible synoptic picture of the various oceanographic factors, the profiles and the stations along them should be spaced as closely as possible, and in order to obtain data that is as homogeneous as possible, the distances and the time intervals should be kept constant. Bjørn Helland-Hansen (1939) has indicated in his work with the ARMAUER HANSEN in the Norwegian Sea how difficult it is to fulfill these conditions of a quasisynoptic survey and how careful one must be in interpreting such observations.

With a single ship at disposal, it is difficult to reach a satisfactory compromise between two conflicting requirements. To fulfill the requirement of a *synoptic* survey the area under investigation should be covered in the least possible time. To obtain great *accuracy*, the number of stations in the area should be as numerous as possible. It is only by working a great number of ships simultaneously that the conflicting requirements can be met to a certain extent.

There is still another difficulty which is of no less importance but which has been neglected hitherto; in fact, it can even make the observations of an oceanographic survey completely worthless and meaningless. Here we refer to the difficulties associated with periodic variations of temperature and salinity (as well as other oceanographic factors). Although these variations occur in a more or less regular

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form, nevertheless they are capable of completely confusing the picture. In the following simple case I will discuss this problem more thoroughly.

THEORETICAL COMPUTATIONS

Let temperature (respectively salinity) at any point in an ocean vary periodically with time in such a manner that

$$T = T_o + a_1 \cos \frac{2\pi}{24} (t - \varepsilon_1) + a_2 \cos \frac{2\pi}{12} (t - \varepsilon_2) , \qquad (1)$$

where t is time in hours. The time variations of T result from a superposition of two waves, one of which is diurnal (period = 24 hours), the other semidiurnal (period = 12 lunar hours). The temperature T_o, the amplitudes a_1 and a_2, and the phases ε_1 and ε_2 (expressed in hours) depend upon the position x, y and the depth z. We do not have to specify the origin of these variations; for instance, they may be internal waves with a tidal period, or in the case of large horizontal temperature and salinity gradients they may be caused by the advection of different water bodies by the periodic tidal currents.

Let a ship occupy a profile along the x-axis starting at time $t = 0$ from a point x_o; at specific intervals there will be oceanographic stations (serial observations). If c denotes the average speed of the ship in knots, taking into account the duration of the stations, the position at time t is given by

$$x = x_o + c\,t . \qquad (2)$$

Should the ship register the temperature continuously, the observed variations would be given by

$$T = T_o + a_1 \cos \frac{2\pi}{24c} (x - x_o - \varepsilon_1 c) + a_2 \cos \frac{2\pi}{12c} (x - x_o - \varepsilon_2 c) . \qquad (3)$$

Therefore the observed temperature distribution of the profile would be periodic, although the mean temperature distribution does not show periodicities. The lengths of these simulated temperature waves would be 24 c n.m. and 12 c n.m. respectively. Should the ship occupy intermittent oceanographic stations (serial observations) at the points x_n, which are at constant distances from each other, the temperature T_n observed there will be given by

$$T_n = T_o + a_1 \cos \frac{2\pi}{24c} (x_n - x_o - \varepsilon_1 c) + a_2 \cos \frac{2\pi}{12c} (x_n - x_o - \varepsilon_2 c) . \qquad (4)$$

The observed temperatures are critically dependent on the selection of x_n, and it might prove difficult to disentangle the temperature distribution thus obtained.

One might then raise the question: Is it possible to select x_n in such a manner that the effect of the semidiurnal tide vanishes or is at least greatly reduced? One would expect the former to be the case if the condition

$$\frac{2\pi}{12c}(x_n - x_o - \varepsilon_2 c) = (2n - 1)\frac{\pi}{2} \tag{5}$$

be fulfilled. In this case the position of the stations would be given by

$$x_n = 3c\,(2n - 1) + (x_o + \varepsilon_2 c)\,, \tag{6}$$

or the distance between two successive stations by

$$x_{n+1} - x_n = 6c\,, \tag{7}$$

provided ε_2 remains constant along the profile. Therefore, the spacing of the stations depends *only* upon the speed of the ship c. For instance, with a ship speed of 8 knots the required distance of the stations is 48 n.m., a typical distance for oceanographic surveys.

From (1) and (2) it follows that stations will be occupied at times

$$t_n = \varepsilon_2 + 3\,(2n - 1)\,; \tag{8}$$

so that the time interval between two stations equals

$$t_{n+1} - t_n = 6^h\,. \tag{9}$$

At the start of the profile, the phase ε_2 is not generally given, and it is not possible to indicate beforehand the station times required for the complete elimination of the semidiurnal wave. If $t_n - \varepsilon_2 = 3^h, 9^h, 15^h$, etc., the semidiurnal wave will vanish; if $t_n - \varepsilon_2 = 0^h, 6^h$, etc., the semidiurnal wave will remain unchanged. If the time of the stations is selected freely, the probability that the effect of the semidiurnal wave in the values will be reduced to ¼, to ½ and to ⅔ is 17, 33 and 67 per cent. Therefore, in the case of a succession of stations with intervals of 6 hours, a more or less large portion of the semidiurnal wave will remain in the station values.

If one wishes to eliminate the semidiurnal wave *completely*, this can be done only if all stations are occupied at the same phase-time of this wave; i. e., the difference in time must be independent of the speed of the ship c, and must always be 12 hours. In this case the values at *all* stations differ from the mean value by the same constant amount; there will be no oscillating disturbance.

If one takes the stations at intervals of more than 6 hours (about 7 or 8), the effect of the semidiurnal wave increases gradually from small amounts to larger according to the value of ε_2, and after having reached a maximum it decreases again. In this case, for instance, it would be possible that the effect of the semidiurnal wave is small in the first part of the profile but large in the second, or vice-versa.

In assuming that there are stations at a time interval of 6 hours, it follows from (4) that there will be at stations x_n, besides the reduced semidiurnal wave, a diurnal effect in the form:

$$T_n = T_o + a_1 \cos \frac{\pi}{4} (2n - 1) - \frac{\varepsilon_1 - \varepsilon_2}{3}. \tag{10}$$

It is remarkable that these values are independent of the speed of the ship. Every *fourth* station will show a maximum of temperature so that local variations of temperature are simulated. However, they have nothing to do with the actual temperature distribution in the ocean. Such errors are present in all oceanographic observations, and they can become extremely important if the tidal influence on the oceanographic factors is large. In such cases phenomena are simulated which depend exclusively upon the speed of the ship and the distance between stations.

Until now we have supposed, in a special case, that ε_1 and ε_2 are constant; i. e., that the tide waves have a direction of propagation perpendicular to the profile. But for the general case, the cotidal lines of the semidiurnal wave cut the direction of the profile by an angle α, and ε_2 is dependent upon x. To determine ε_2 we have to consider only the component $c'/\sin \alpha$ of the velocity of the tidal wave in the direction of the ship movement. Analagous with the Doppler effect, it is easy to show that the time interval between stations required for the complete elimination of the semidiurnal wave is

$$t_{n+1} - t_n = 12/\left(1 - \frac{c}{c'} \sin \alpha\right). \tag{11}$$

The value of c' is approximately 150 knots and the ratio c/c' a small number. The effect in all cases is small, especially since profiles are mostly perpendicular to coast lines, α thus being a small angle.

In the following example let ε_2 have a constant value of 3 hours. A ship takes oceanographic stations every 6 hours at a distance of 40 n.m. The average speed of the ship is 40/6 knots. According to equation (8) the effect of the semidiurnal tide wave will be completely eliminated if the times at the stations are 0^h, 6^h, 12^h, 18^h; it is reduced by 50 per cent if the station times are 5^h, 11^h, 17^h, 23^h. In addition there will be a considerable influence of the diurnal wave, especially if the diurnal wave is large compared to the semidiurnal wave. In the observations, highest and lowest temperatures occur at an interval of 4 stations. These influences thus simulate local disturbances in the temperature (and salinity) field. Dynamic computation based on such temperature and salinity values are subject to similar errors.

THE CRUISES OF THE MARINE LIFE RESEARCH PROGRAM

The Marine Life Research Program[3] of the Scripps Institution of Oceanography, University of California, includes an oceanographic survey of the west coast of America between 25° and 43° N. Cruises involving three ships have been made at regular intervals of about a month since February 1949. Each cruise lasts about 15 days and is composed of 12 profiles perpendicular to the coast about 140 n.m. apart. At each station the normal serial observations extend to a depth of 1,200 m. For each survey, charts of the horizontal distribution of all oceanographic factors are given, among them a chart of the dynamic height of the sea surface relative to the 1,000 decibar surface, with an interval of 5 dyn cm (S.I.O., 1949).

The main purpose of this extensive oceanographic survey is to obtain an insight into the circulation variations in this area, which is characterized by the California Current. During my visit at the Scripps Institution of Oceanography the various quasisynoptic charts of the oceanographic elements of the first profiles were submitted to me for discussion. In general they showed the California Current running southward. Moreover, on the maps surprising disturbances in the form of cyclonic and anticyclonic eddies seemed to be superimposed upon the California Current.

A close inspection of the dynamic topographies of the surface showed that these eddies succeed each other along the profiles at approximately equal intervals. Similar intervals exist in the corresponding disturbances in the temperature and salinity distribution. This made me suspect that these eddies are simulated disturbances rather than real. This idea was supported by the fact that the average time interval from one station to another is about 6 hours, whereas the distances between the stations was 40 n.m. Consequently the average speed of the ship is 40/6 knots, and this value fulfills in a remarkable way equation (7). This corresponds to the case discussed previously, and the occurring eddies at an interval of about 4 stations (160 n.m.) would be due to the influence of a diurnal wave. Any possible influence of a semidiurnal wave would be weakened by the selected spacing of stations and the speed of the ship. In fact, most of the profiles scarcely showed the influence of the semidiurnal wave. Aside from the fact that the station spacing and ship speed would naturally favor the diurnal over the semidiurnal wave, as they appear in the observations, there are reasons why the diurnal wave should be of larger amplitude in the ocean off the California Coast. One reason is that the tide observations along this coast show a pronounced diurnal character. Another reason follows from the theory of internal waves (Defant, 1940; Sverdrup, et al., 1942), according to which the period T of free internal oscillations is given by relation

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[3] This program represents part of the Cooperative Sardine Investigation of the west coast, the latter including two other state agencies of California and a division of the U. S. Fish and Wildlife Service.

$$T = \frac{T_e}{\sqrt{1 + T_e^2/T_o^2}}. \tag{12}$$

Here T_o is the period of free oscillations on a nonrotating earth, and $T_e = 12/\sin \zeta = \frac{1}{2}$ pendulum day is the period of the inertia oscillations. For the ocean region under consideration, the magnitude of T_o is 150–200 hours, so that $T_e/T_o = 0.1$ and $T \approx T_e$. Since the area under investigation extends from 40° to 25° N, the period of inertia oscillations varies between about 20 and 25 hours. For Lat. 30° N it is exactly 24 hours. Since the diurnal and semidiurnal tide waves, which are forced waves, have periods of 24 and 12.43 hours respectively, the diurnal waves will be increased by *resonance.*

THE TIDAL EFFECT IN OBSERVATIONS AT THE SCRIPPS PIER

It would be desirable to check these conclusions by means of anchor stations, for according to the results of those taken on the METEOR Expeditions over the West African shelf, 1937 and 1938, such tidal influence is probable (Defant 1937, 1948). But unfortunately no such anchor stations are available. However, for numerous years temperature recordings have been taken at the end of Scripps Pier at depths of 2 and 16 feet above bottom (water depth 18 feet). Leipper (1949), in discussing these observations, has pointed out the existence of large quasiperiodic variations in which the tidal periods seemed to be especially prevalent. In examining the tidal influence numerically, I have subjected the observations for August 28 through 31, 1927 (represented in fig. 2 of Leipper's paper) to harmonic analysis and have compiled the results in Table I (see also Fig. 1).

The tidal influence is very pronounced. The tide and temperature curves are almost completely reversed, and the phase differs by half a period. The variation in temperature with semidiurnal tide in the surface and bottom layers attains an amplitude of more than 3° C; with the diurnal wave in the surface layer it attains a magnitude of only 1° C. The half-hourly bathythermograms made at the end of

TABLE I. HARMONIC ANALYSIS OF OBSERVATIONS TAKEN AT SCRIPPS PIER FROM AUGUST 18 THROUGH 31, 1927 (SEE ALSO FIG. 1)

	Mean value	*Diurnal wave (period = 24 h.)*	*Semidiurnal wave (period = 12 lunar hours)*
Tidal variation in ft.	6.5	$+ 1.32 \cos \frac{2\pi}{24} (t - 16.4^h)$	$+ 2.05 \cos \frac{2\pi}{12} (t - 6.7^h)$
Temp. °C			
16′ above bottom:	17.80	$+ 0.31 \cos \frac{2\pi}{24} (t - 2.9^h)$	$+ 1.69 \cos \frac{2\pi}{12} (t - 0.6^h)$
at the bottom:	17.76	$+ 0.18 \cos \frac{2\pi}{24} (t - 12.8^h)$	$+ 1.74 \cos \frac{2\pi}{12} (t - 11.6^h)$

the pier during two days (fig. 20 of Leipper's paper) prove that the entire water mass in the vicinity of the coast is subjected to this tidal influence, the boundary layer rising and falling with an amplitude of over 7 feet. According to all these observations, periodic variations exist in both temperature and salinity in the entire water column and they follow the tides.

ELIMINATION OF TIDAL EFFECT FROM OBSERVATIONS OF THE MLR CRUISES

According to the foregoing considerations, it is most probable that the observations made off the California Coast include tidal influence, this influence being primarily responsible for the complicated structure of the dynamic topographies. The semidiurnal influences are weaker than the diurnal ones, and they are further suppressed by the selected distances between stations and the average ship speed. To obtain an undistorted dynamic topography of this surface, an effort should be made to eliminate the diurnal component also. A method for this is now given.

The method is much more complicated if some residues of the semidiurnal disturbance are left. The difficulty of completely eliminating the disturbances is dependent on three considerations. In the first place, the extent of these tidal influences varies according to localities, and consequently one must take into consideration many irregularities. Secondly, the distance between stations as well as their duration are subject to irregular variations which, although not great, change the *average* speed of the ship somewhat. The indicated anomaly of dynamic height at a station refers to a time interval of about 1 to 1½ hours, and this uncertainty as to time and locality enters fully into the observational values. In this one recognizes that the time values can

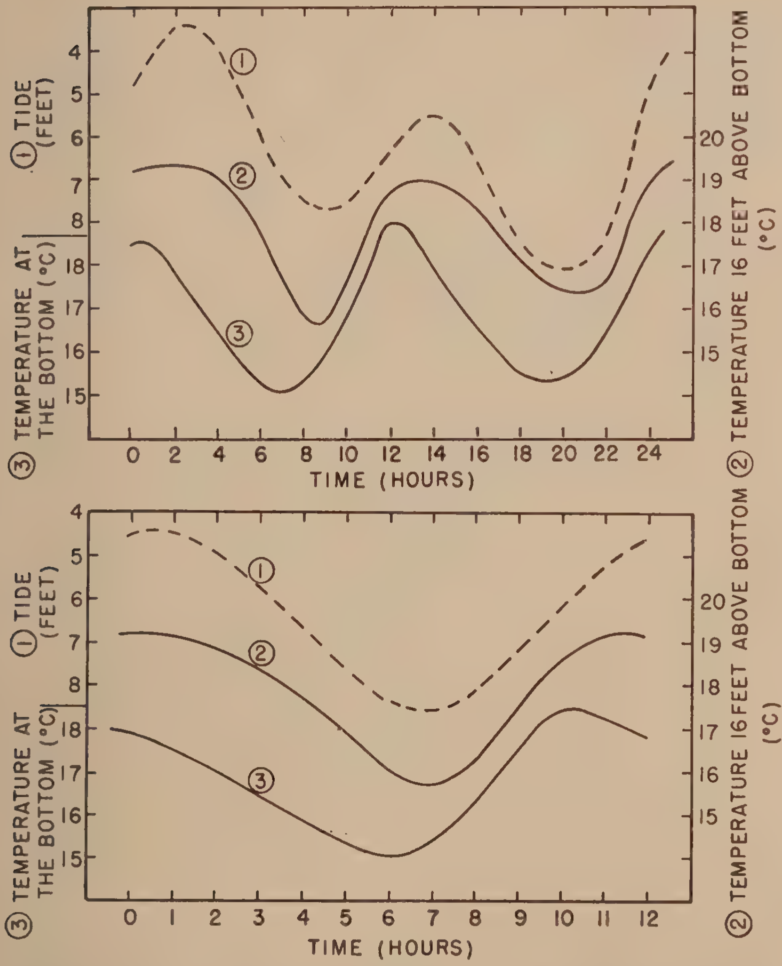

Figure 1. Above: Mean tidal curve for the period from August 28 through 31, 1927, and simultaneous temperature variations at the bottom and 16 ft. above the bottom at the end of the Scripps Pier at La Jolla, California. Below: Mean semidiurnal tide (period 12 lunar hours) and corresponding temperature variations for the same time at the end of the Scripps Pier at La Jolla, California, 16 ft. above the bottom.

have a margin of error of ± 1 hour. Thirdly, the tidal disturbances are superimposed on an average dynamic topography of the sea surface which is unknown at first. These circumstances make it necessary to proceed by trial and error, but the following method has proved to be workable.

Fig. 2 shows the dynamic topography of the sea surface during the first cruise, including large eddies associated with the diurnal tide. The steps taken in separating the fundamental part from the tidal influence will be shown by means of profiles 500, 800 and 1200. Tables II and III give all of the data of profiles 500 to 800 as well as the average difference in time (~ 6 hours) and the distance between stations (~ 40 n.m.) Figs 3 and 4, in their upper part, show the observed values of dynamic height along the profiles at various sta-

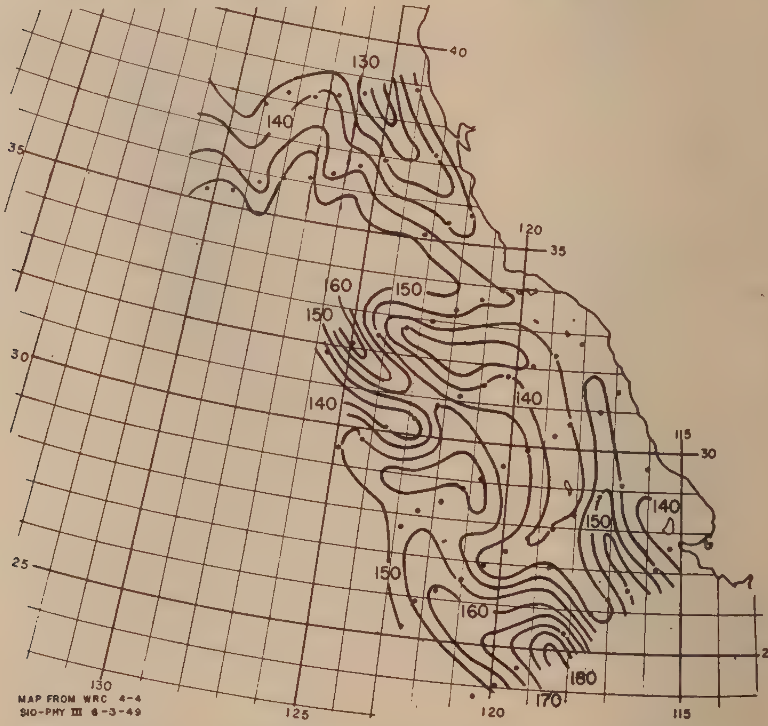
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Figure 2. Marine Life Research Cruise 1 (Feb. 28 to Mar. 15, 1949): Dynamic height anomalies (0 over 1000 Decibars). Contour interval 5 dyn cm. The nearly normal lines to the coast are numbered consecutively from north to south, the southernmost line shown being the 1200 series.

TABLE II. CRUISE 1. (FEBRUARY 28–MARCH 16, 1949): PROFILE 500

Station	*Date*	*Mean time GCT*	*Time-difference*	*Distance between stations in n.m.*	*Dyn. height Dyn. m.*	*Dyn. height from smooth curve*	*Difference Dyn. m.*	*Effective Time*
501	1. III	9.5h			1.401	1.303	+ 0.098	+ 1.5h
			5.8h	46				
502		15.3			[1.280]	1.320	− .040	− 3.2
			5.8	45				
503	1. III	21.1			1.262	1.336	− .074	− 2.9
			6.8	40				
504	2. III	03.9			1.393	1.352	+ .041	+ 3.9
			6.8	45				
505	2. III	10.7			1.366	1.370	− .004	+ 1.3
			6.5	42				
506	2. III	17.2			[1.340]	1.387	− .047	− 5.2
			7.6	40				
507	3. III	00.8			1.379	1.396	− .017	+ 0.8

TABLE III. CRUISE 1. (FEBRUARY–MARCH 16, 1949): PROFILE 800

Station	*Date*	*Mean time GCT*	*Time-difference*	*Distance between stations in n.m.*	*Dyn. height Dyn. m.*	*Dyn. height from smooth curve*	*Difference Dyn. m.*	*Effective Time*
808	14. III	06.6^h			1.534	1.558	– 0.024	-2.4^h
			7.9^h	38				
807		14.5			1.638	1.512	+ .126	+ 5.5
			6.2	39				
806		20.7			1.480	1.468	+ .020	+ 0.3
			5.5	34				
805	15. III	02.2			[1.370]	1.420	– .050	– 5.3
			7.4	40				
804		09.6			1.400	1.390	+ .010	+ 0.6
			6.6	40				
803		16.2			1.415	1.366	+ .049	+ 4.8
			5.6	46				
802		21.8			1.412	1.424	– .012	– 1.8
			5.4	39				
801	16. III	03.2			1.468	1.486	– .018	– 6.0

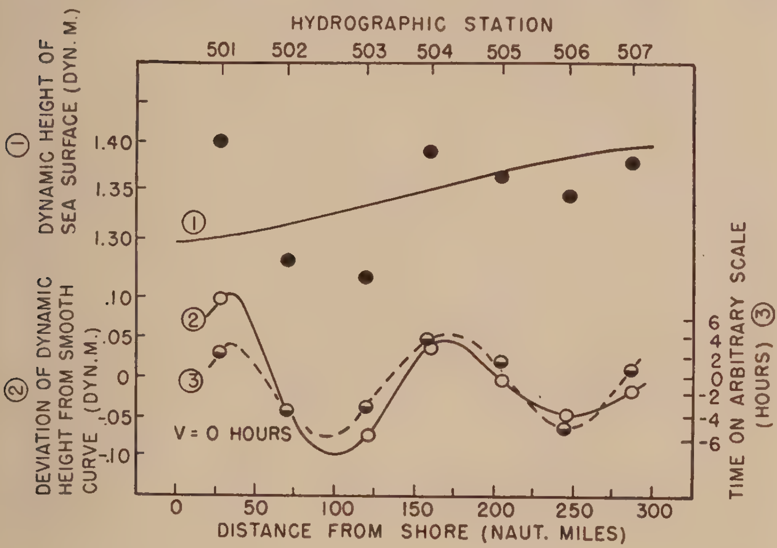


Figure 3. Cruise 1, Stations 501–507: Above: Dynamic heights at stations and smooth curve along the line. Below: Deviations of dynamic heights from the smooth curve (solid line) and effective times (dotted line) along the entire profile.

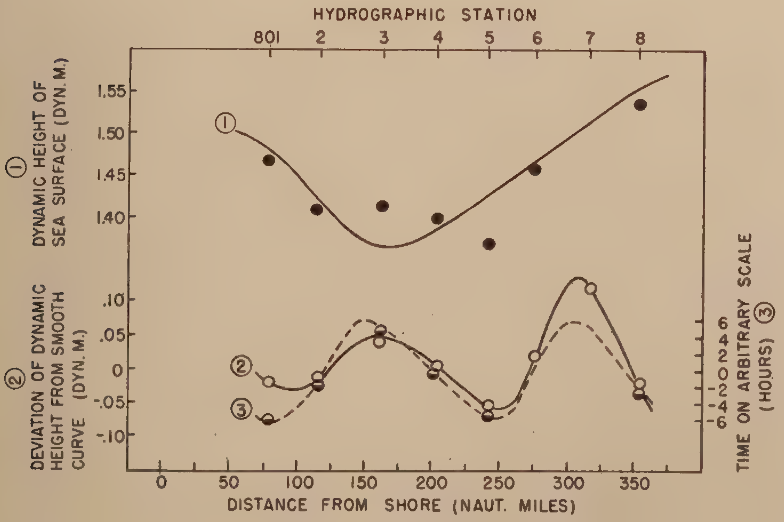


Figure 4. Same as Fig. 3 for stations 801–808.

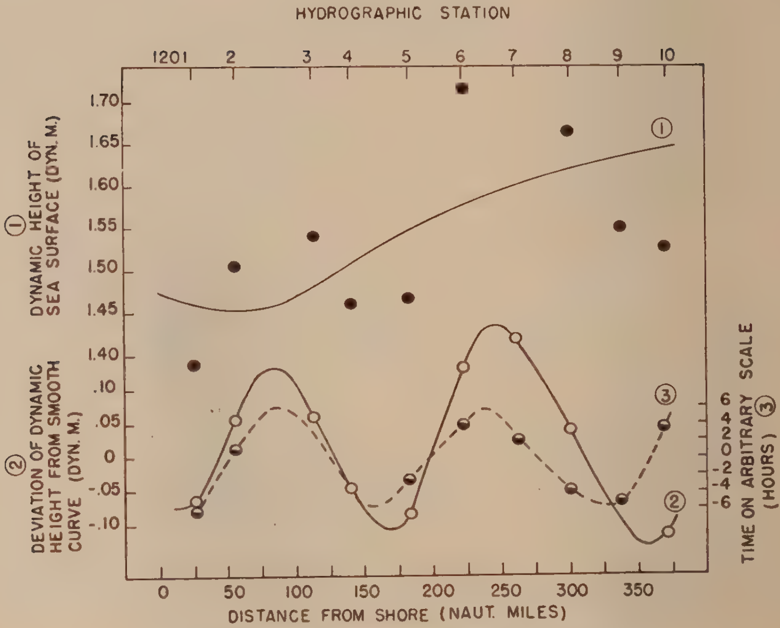


Figure 5. Same as Fig. 3 for stations 1201–1210.

tions at the correct distance from the coast. Through these values we draw a smooth mean curve which corresponds to the average dynamic topography that was prevailing when the profile was made. The deviations from this curve will show the tidal influence. To emphasize this tidal influence, it is advantageous to change the local time to an effective tidal time. We assume that the maximum positive effect of the tide always occurs at + 6 hours, the maximum negative effect at $18^h = -6$ hours, with no effect at 0 and 12 hours. At n hours before and after 6 hours the effect is equal, provided conditions are symmetrical. Therefore, this time n is considered as the effective time according to the following scheme:

Tidal time	0^h	1	2	3	4	5	6	12^h	13	14	15	16	17	18
	12^h	11	10	9	8	7		24^h	23	22	21	20	19	
Effective time	0^h	+1	+2	+3	+4	+5	+6	0^h	−1	−2	−3	−4	−5	−6

The effective time is a *relative* measure of tidal influence. The effective times of profiles 500 and 800 are contained in Tables II and

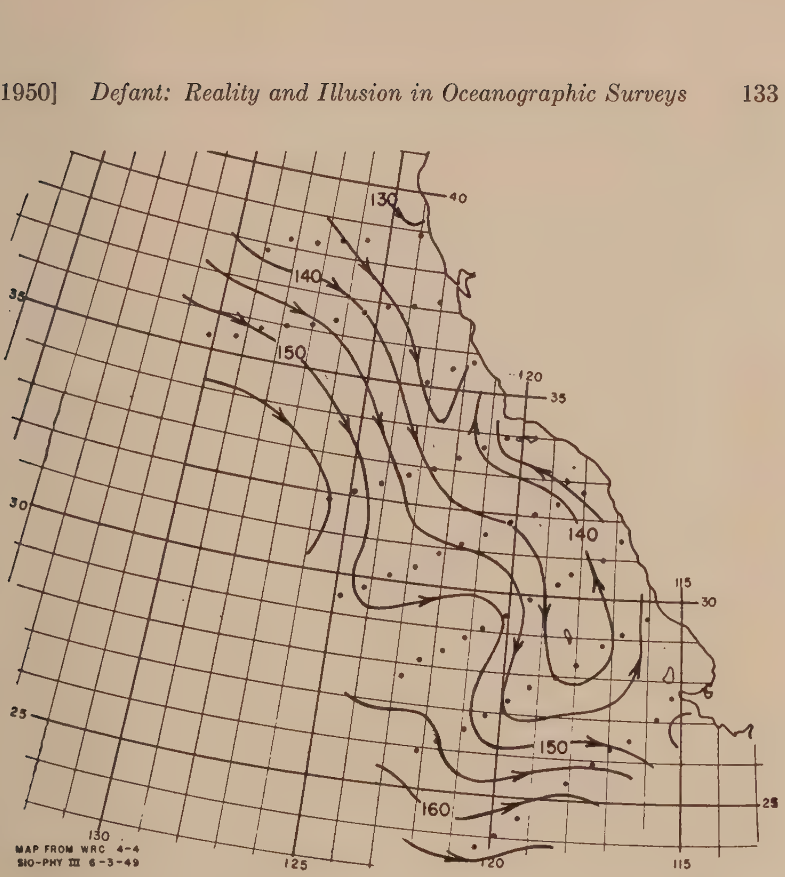
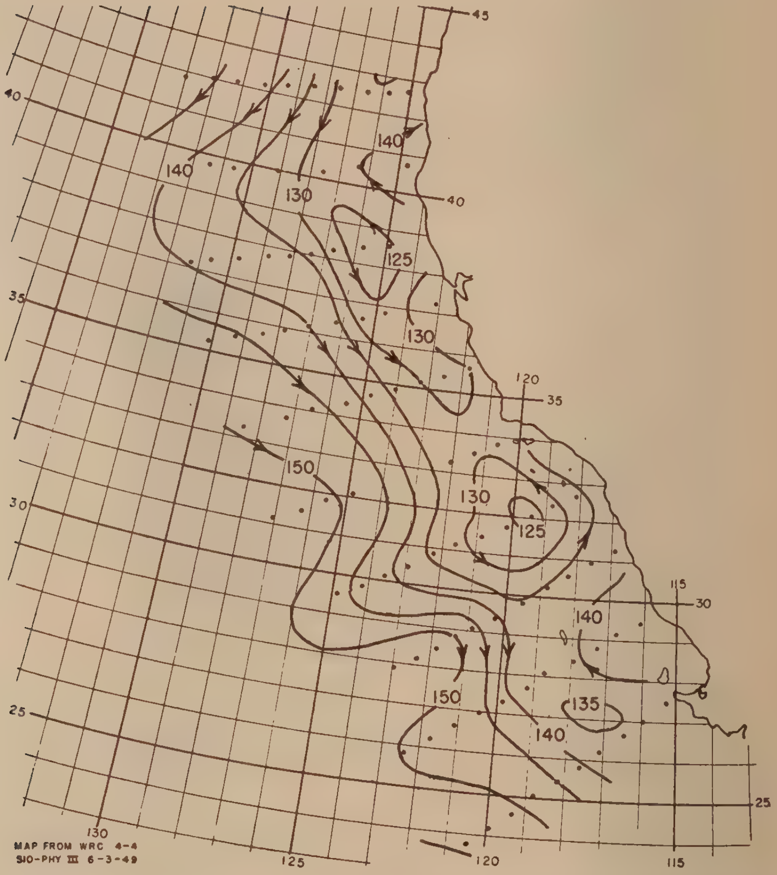


Figure 6. Cruise 1 (Feb. 28 to Mar. 15, 1949): Dynamic height anomalies (0 over 1000 Decibars) after elimination of tidal effect. Contour interval 5 dyn cm.

III. The scale of local time is shifted so that the effective time 6 hours corresponds to the maximum positive effect of tide. The drawing of the mean (basic) curve, the deviations of the station values from this mean curve, and the shift of the time scale, are mutually dependent, and one must seek the best compromise. This might be done quite objectively if the effect of the tide were constant with respect to time and locality, but since this is not the case we have proceeded by trial and error.

The full drawn curve in the lower part of Fig. 3 gives the distribution of deviations from the mean curve, whereas the dashed curve gives the effective times, here incidentally without a displacement of the time scale. The good agreement between both curves shows the relation


45
40
140
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125
35
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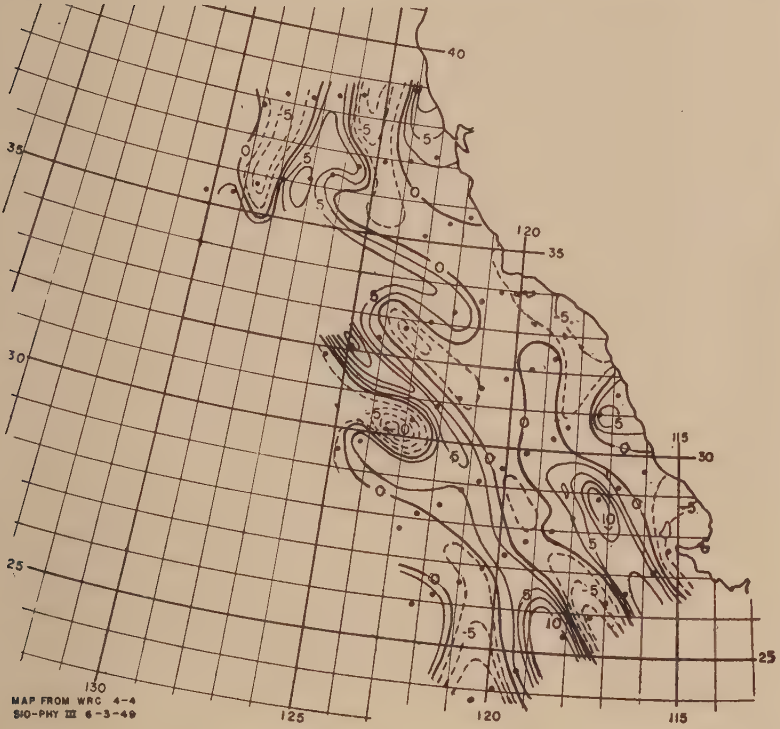
130
125
115
30
140
135
25
150
140
25
130
MAP FROM WRC 4-4
SIO-PHY III 6-3-49
125
120
115

Figure 7. Cruise 2 (Mar. 28 to Apr. 12, 1949): Dynamic height anomalies (0 over 1000 Decibars) after elimination of tidal effect. Contour interval 5 dyn cm.

between deviations and tides. The profiles 800 and 1200 (Figs. 4 and 5) have been analyzed in the same manner, except that it was necessary to shift the time scale. Not all profiles show equally good agreement, and it is often necessary to adjust the basic curve repeatedly in order to reach the best compromise. In trying to make the curves of the deviations correspond to the curves of effective times, no attention should be given to the amplitude of the time curve, for the values are



MAP FROM WRC 4-4
SIO-PHY III 6-3-49

Figure 8. Distribution of deviations in dynamic heights caused by tides for Cruise 1 (0 over 1000 Decibars). Tidal effect: + above, – below the mean dynamic topography. Contour interval 2½ dyn cm. Full curves +, dashed curves –.

relative. Only the position of maxima and minima and the point of inflexion should coincide. In most cases this can be achieved, but the accuracy of the quantities, which have to be shifted, is ± 1 hour at most.

If there is a definite semidiurnal effect in the deviations of station values from the basic curve, then it is necessary to subject these values to harmonic analysis if we wish to designate this effect as a tidal effect and if we wish to separate semidiurnal and diurnal influences from one another. The work connected herewith increases considerably but it can hardly be avoided.

In this manner all of the profiles of a cruise can be analyzed so that

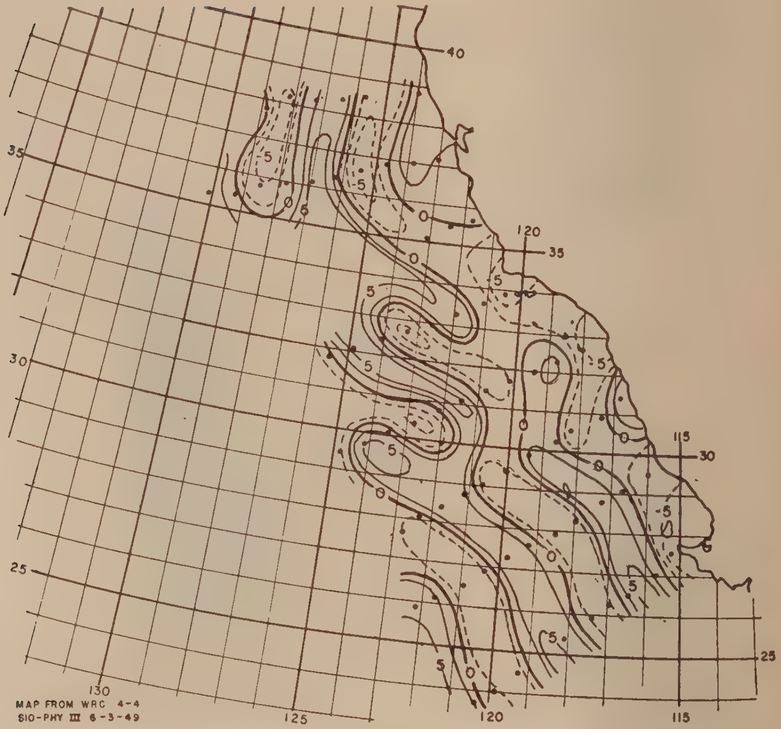


Figure 9. Time of stations (Cruise 1) expressed in effective time (6^h = maximal positive, -6^h = maximal negative effect). Contour interval $2\frac{1}{2}^h$.

one obtains the dynamic topography of the sea surface with tidal influences eliminated. The individual values of stations of the first cruise for the distribution of dynamic heights above 1000 decibars are shown in Fig. 6. In this figure one notices at once the extent of simplification. Off the entire California Coast, at a distance of 100–150 n.m., there is a trough where the physical ocean surface is low; toward the open ocean and toward the coast the surfaces rise fairly uniformly, which correspond to the California Current in a SSE direction on the one hand and to a coastal countercurrent to the NNW just off the coast on the other hand. The trough between both currents is probably connected with the phenomenon of upwelling and will be subject to variations.

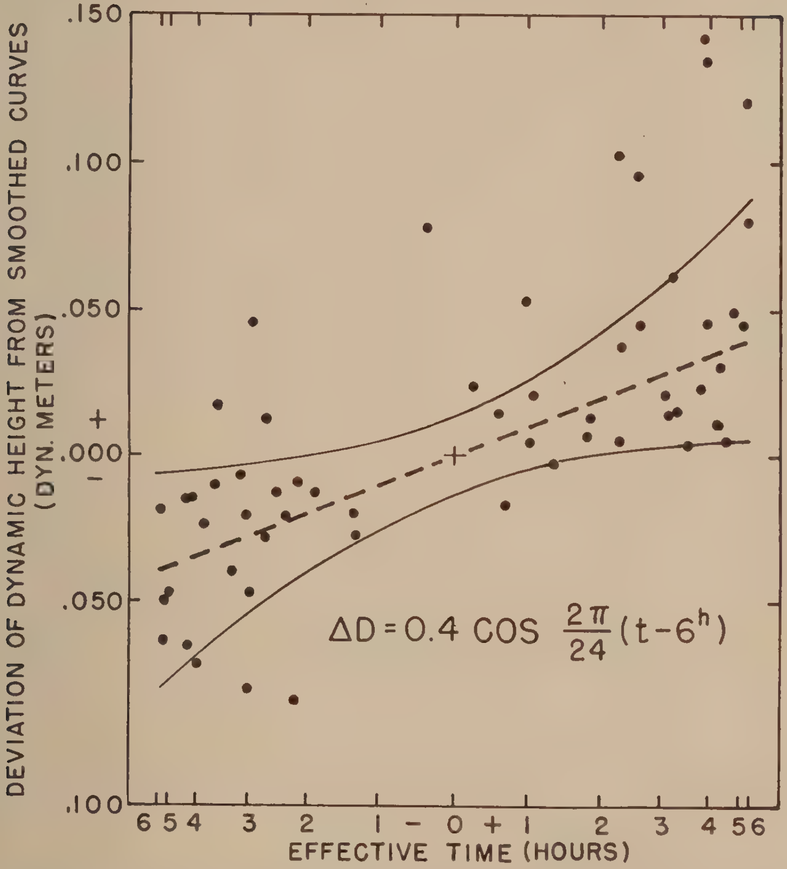


Figure 10. Relation between deviations of dynamic heights from the mean dynamic topography and the effective times.

Once the dynamic charts of all cruises are freed from extraneous influences, the basic data will be available for study of the system of currents off the entire area during intervals between cruises, and it will be possible to go into problems regarding the causes of these variations. That such variations in the dynamic topography actually occur can be seen by a comparison with the dynamic topography of the second cruise (March 28–April 12, 1949), which is given in Fig. 7.

However, we will not go into any further discussion of these variations here.

It may still be of interest to examine the correlation that exists between the disturbances caused by conditions of survey and the effective times that determine the tidal influences. The best approach is to compare charts which indicate the geographical distribution of these two quantities (see Figs. 8 and 9). It will be seen that the appearance of the two charts is similar, and there is no better proof that these disturbances are caused by tides. Theoretically we can expect a relationship of the form $\Delta D = m \cos 2\pi/24\ (t - 6^h)$; such a relationship is actually found (Fig. 10). Approximately, it follows that $m = 4$ dyn cm. Therefore the disturbances caused by the tides can reach a maximum of 8 dyn cm, compared to a difference of 10 dyn cm between the trough and the left-hand side of the current in Fig. 5.

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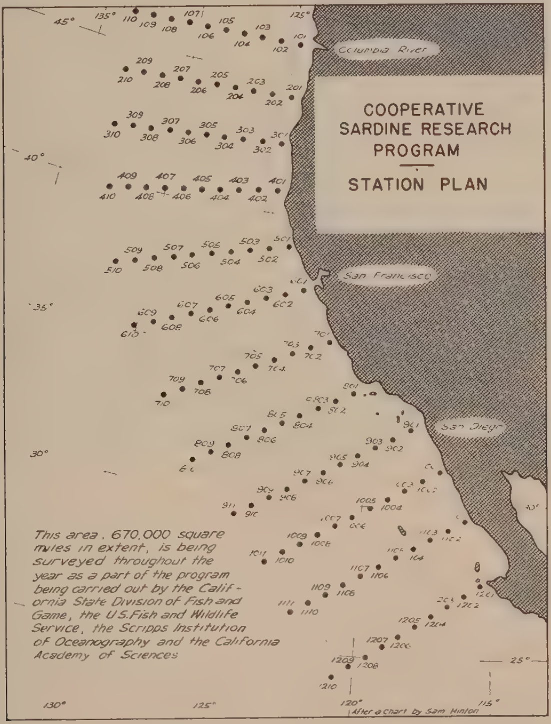
Contribution No. 479

INCREASING ABUNDANCE OF ALBATROSSES OFF THE COAST OF CALIFORNIA

By J. L. McHUGH

The three albatrosses of the north Pacific, *Diomedea nigripes* (the Black-footed), *D. immutabilis* (the Laysan), and *D. albatrus* (the Short-tailed) have all been recorded in the past as abundant off the Californian coast. By 1924, however, their numbers had greatly decreased, the Short-tailed to the point of extinction (Anthony, 1924). The Black-footed Albatross made a noticeable recovery in the fifteen years preceding 1944 (Grinnell and Miller, 1944) and recent observations suggest that this increase is continuing. A search of the literature reveals no records of *D. albatrus* and only two of *D. immutabilis* from this area since early in the twentieth century.


COOPERATIVE SARDINE RESEARCH PROGRAM

STATION PLAN

This area, 670,000 square miles in extent, is being surveyed throughout the year as a part of the program being carried out by the California State Division of Fish and Game, the U.S. Fish and Wildlife Service, the Scripps Institution of Oceanography and the California Academy of Sciences

After a chart by Sam Hinton
Columbia River
San Francisco
San Diego
45°
40°
35°
30°
25°
135°
130°
125°
120°
115°
110 109 108 107 106 105 104 103 102 101
210 209 208 207 206 205 204 203 202 201
310 309 308 307 306 305 304 303 302 301
410 409 408 407 406 405 404 403 402 401
510 509 508 507 506 505 504 503 502 501
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710 709 708 707 706 705 704 703 702 701
809 808 807 806 805 804 803 802 801
911 910 909 908 907 906 905 904 903 902 901
1011 1010 1009 1008 1007 1006 1005 1004 1003 1002
1111 1110 1109 1108 1107 1106 1105 1104 1103 1102
1210 1209 1208 1207 1206 1205 1204 1203 1202 1201

Fig. 30. Plan of stations visited by vessels from which counts of albatrosses were made.

The last positive record of the Short-tailed Albatross reported by Grinnell and Miller (1944) was in 1898, and these authors suggest that the species may be extinct. This is supported by Austin (1949) and is discussed by Kenyon (1950). It is therefore probable that the more recent records, such as that of Wilder (1940) were based on mistaken identification.

In 1909, a Laysan Albatross was taken off San Nicolas Island, and in 1913 two were seen 600 to 750 miles southwest of San Francisco (Willett, 1913). In 1945, Yocom

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(1947*a*) saw two approximately 500 miles southwest of San Francisco, and Kenyon (1950) collected a specimen in December, 1948, about 75 miles northwest of San Francisco.

In March, 1949, while taking part in cruise 1 of the Scripps Institution vessel "Horizon," the author saw at least two Laysan Albatrosses off central California. The first observation was made at 8:45 a.m. on March 15 at station 803 (fig. 30) and a second bird of the same species appeared at 9:10 a.m. Forty miles closer inshore, at station 802, which was occupied early in the afternoon of the same day, no Laysan Albatrosses were seen, but at station 801, at 6:00 p.m., two appeared and came to rest on the water within fifty feet of the stern of the ship. During the same period, from February 28 to March 14, Laysan Albatrosses were also observed by E. H. Ahlstrom and R. L. Wisner from the Scripps Institution vessel "Crest" and by R. C. Wilson and Warren Wooster from the research vessel of the California State Division of Fish and Game, the "N. B. Scofield," while the former cruised off central California and the latter was off northern Lower California. Although this species is generally more timid than *D. nigripes*, on occasion it approached very close to the vessels (fig. 31).

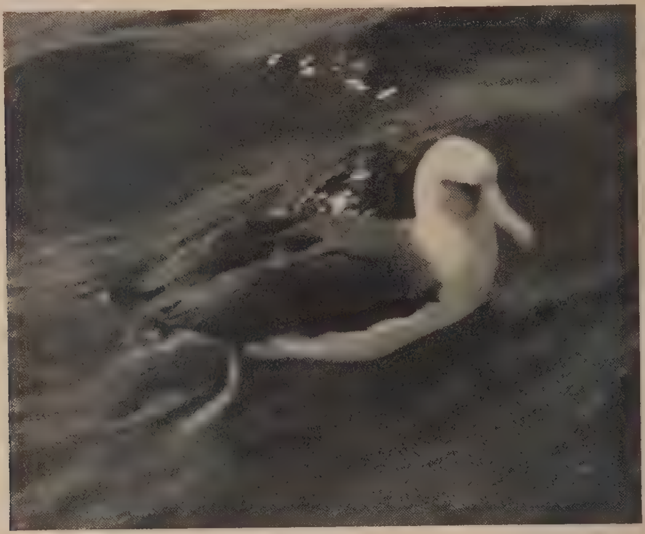

Fig. 31. Laysan Albatross seen at station 1010, 11:30 a.m., March 4, 1949. Photograph by Warren Wooster.

During cruise 2 of the "Horizon," from March 28 to April 11, the following records of *D. immutabilis* were obtained:

	Position		
Date	N. Lat.	W. Long.	Number
March 31	32° 53′	120° 43′	1
April 2	33° 15′	122° 05′	1
April 3	31° 47′	125° 38′	2
April 5	35° 18′	130° 11′	1
April 5	35° 31′	129° 24′	2

The species was also seen off northern Lower California, southern California, northern California and Oregon by scientists on the other two vessels.

At all stations occupied during daylight by the "Horizon" large numbers of Black-footed Albatrosses were seen. The following counts were made during cruise 1:

Station	Date	Time	Maximum number
807	March 14	7:00 a.m.	25
806	March 14	1:00 p.m.	26
805	March 14	6:00 p.m.	22
803	March 15	9:10 a.m.	35
802	March 15	2:00 p.m.	52
801	March 15	6:00 p.m.	55

Most of the birds usually came within a few feet of the ship, especially when garbage was thrown overboard. Since a number of albatrosses always followed the ship closely during the runs between stations, some of those tallied no doubt represented duplications from previous stations. However, on the basis of marking experiments made in 1941 (Miller, 1942), it appears that only a small proportion of the birds seen at one station would follow to the next station, forty miles away. The numbers seen always increased during the period that the ship was at a station, as noted by Yocom (1947*a*) and as illustrated by the following counts made during cruise 2. Station time varied between an hour and a half and three hours, and averaged about two hours. Counts were usually made soon after arrival and just before departure. It will also be noted that the numbers increased from station to station during the day.

Station	Date	First Count		Second Count	
		Time	Number	Time	Number
801	March 29	2:50 p.m.	3	5:00 p.m.	3
802	March 30	2:50 p.m.	3	6:30 p.m.	20
803	April 2	8:25 a.m.	21	10:25 a.m.	30
807	April 3	6:20 a.m.	7	8:30 a.m.	11
808	April 3	12:30 p.m.	11	3:30 p.m.	31
809	April 3	6:30 p.m.	23	7:00 p.m.	41
710	April 4			7:00 p.m.	27
610	April 5	10:40 a.m.	18	12:40 p.m.	27
609	April 5	4:05 p.m.	29	6:00 p.m.	31
606	April 6	9:15 a.m.	7	10:30 a.m.	15
605	April 6			5:00 p.m.	22
602	April 7			9:00 a.m.	36
601	April 7	12:15 p.m.	21	1:30 p.m.	70
702	April 8	7:30 a.m.	21	8:15 a.m.	30
703	April 8			1:00 p.m.	35
704	April 8			7:00 p.m.	42
706	April 9	6:15 a.m.	8	7:30 a.m.	22
707	April 9			12:45 p.m.	32
708	April 9			5:30 p.m.	41

These numbers represent by far the greatest concentrations of *D. nigripes* seen from the Scripps Institution vessels since cruises were resumed after the end of the war. Miller (1940) reported that the greatest number seen at one station during June and August, 1937 and 1938, was thirty-three. Yocom (1947*a*, 1947*b*) listed larger numbers than have been observed by us, but his ship was in an area for periods up to 25 days. Probably as a consequence of this increased abundance along the coast, Black-footed Albatrosses have occurred in 1949 closer to shore than usual, at times within ten miles.

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Scripps Institution of Oceanography, La Jolla, California, December 5, 1949.

Contribution No. 480

Number cancelled.

Contribution No. 481

OCEAN AND OCEANOGRAPHY

by HARALD ULRIK SVERDRUP,
MARTIN WIGGO JOHNSON
and RICHARD HOWELL FLEMING

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AND OCEANOGRAPHY. "Ocean" is the name
ne great connected sheet of water which covers the
of the surface of the earth. But the ocean is
hydrosphere in so far as the latter term includes
er lying on or flowing over the surface of the land.
on of an encompassing ocean bounding the habitable
d in the creation myths of the most ancient civiliza-
Babylonians looked on the world as a vast round
ng from the midst of a universal sheet of water. In
scriptures the waters were gathered together in one
vord of God, and the dry land appeared. The Ionian
ooked on the circular disk of the habitable world
d by a mighty stream named Oceanus, the name of
god, father of gods and men, and thus the bond of
n heaven and earth.

Pythagorean school of philosophy upheld the spheri-
t the disk-shaped world, some of the ancient geog-
uding Eratosthenes and Strabo, looked upon the
as forming two belts at right angles to each other,
cean following the equator, the other surrounding
n pole to pole as in the *terra quadrifida* of Macro-
thers, including Aristotle and Ptolemy, looked upon
land, or *oikoumene,* as occupying the greater part of
rface. Until the discovery of America and of the
the belief was general that the land surface was
the water surface. (*See* MAP.) Only in the 19th
he existence of the southern continent been demon-
the limits of Antarctica.

hy is the science which deals with the ocean. Of re-
use of "hydrography" as the equivalent of physical
has acquired a certain currency, but as the word is
more than one other meaning (*see* SURVEYING) it
e used for oceanography.

Research and Organization.—Research in ocean-
n in recent times, especially since the rapid in-
tudy of the exact sciences during the 19th century.
at sea with accurate instruments became common,
' logs of today are provided with headings for
observations of the phenomena of the sea-surface.
of the sailors' scientific logs were brought together
thusiast in the study of the sea, Matthew Fontaine
-73), whose methods and plans were adopted at
congresses. Many millions of observations are
ips' logs; this firsthand material is preserved in
ices of various nations. The contents of these logs,
er more to maritime meteorology than to ocean-
rly so called.

al for the study of the surface phenomena of the
n supplemented in relation to the study of the
cean, by the records of numerous scientific expedi-
rly by publications embodying systematic observa-
nanent basis. Valuable observations were made in
during the expeditions of Captain James Cook and
orers, especially those of Sir John Ross in the
James Ross in the south. The period of deep sea
began about 1850 when it became possible to
depths with precision. (*See* SOUNDING.) At this
knowledge of the depths of the ocean assumed an
ractical importance for the laying of telegraph
ttom of the sea. Another stimulus came from the
began to realize the importance of a more detailed
the life conditions of organisms at great depths

inary trips of scientific marine investigation were
greatest purely scientific expedition ever under-
ge of H.M.S. "Challenger" round the world under
irection of Sir Wyville Thomson and the naval
ir George Nares. This epoch-making expedition
ristmas 1872 to the end of May 1876, and gave
d general view of the physical and biological con-
cean as a whole. Almost simultaneously with the
German expedition in S.M.S. "Gazelle" conducted observations in the South Atlantic, Indian and South Pacific oceans; and the U.S.S. "Tuscarora" made a cruise in the North Pacific, sounding out lines for a projected Pacific cable. Since that time investigation has been carried out by ships of all nations, on a scale too extensive for detailed record.

In 1902 at Stockholm was founded the International Council for the Study of the Sea, whose headquarters are in Copenhagen. The idea is to help and control the fisheries in the Baltic, the North sea, the Norway sea and Barents sea, as well as in British and Irish waters. Besides the northwestern European states Portugal, Spain and Italy have also become members of this union, which has done much to improve the instruments and methods of oceanography. Generally, each government has built or fitted out a research steamer for the work. The United States of America, Canada and Japan also take part.

Surface of the Ocean.—If the whole globe were covered with an ocean of uniform depth and at rest, the surface would form a perfect ellipsoid of revolution. But the water surface is broken by land, and the mean density of the substance of the land is 2.6 times as great as that of sea water, so that the gravitational attraction of the land must necessarily cause a deviation of the plumb line toward the continent. Hence, the geoid or figure of the ideal sea surface is not part of an ellipsoid of rotation but is somewhat irregular. Recent pendulum observations have shown great local differences in density in the earth's crust, a marked deficiency of mass under high mountains and excess under the bed of the ocean. The intensity of gravity at the surface of the sea far from land has been measured on several occasions and has been found to be normal. The inequalities of the geoid are not more than 100 m.

In the absence of other forces the sea surface would always coincide with the geoid, but distortions of the ocean surface arise from the effect of the tide-producing forces and from meteorological causes and may be periodic or unperiodic in their occurrence. Except for the tides, they do not amount to more than one or two metres. The atmosphere affects sea level by its varying pressure. Atmospheric precipitation poured into the sea by the great rivers must necessarily maintain a permanent rise of the sea level at their mouths, and from this cause the level around the coasts of rainy lands must be higher than in mid-ocean. The Baltic is fuller in the time of the summer rains than in winter, when the rivers and lakes are frozen and most of the precipitation on the land is snow. A similar range occurs on the Netherlands coast in the North sea, where the maximum level is reached in October, the month of highest rainfall, and there is a range of 200 mm. to the minimum level at the time of least rainfall in early spring. Heating and cooling of the surface layers are accompanied by expansion and contraction and also lead to rhythmic variation of sea level.

In the monsoon regions the half-yearly change from onshore to offshore winds produces noticeable differences in level, the total range being 237 mm. The influence of wind on water level is most remarkable in heavy storms on the flat coasts of the North sea and the Baltic, when the rise may amount to many feet. In the region of tropical storms the extreme winds may cause a heaping-up of water capable of devastating the low coral islands of the Pacific. The old speculations as to a great difference of level between the Mediterranean and the Red seas have been proved by precision levelling to be erroneous.

Deviations from the geoid amounting to more than one metre are also related to the presence of the permanent ocean currents as described below.

Land and Water.—The ocean waters are continuous around the antarctic, and the names Atlantic, Pacific and Indian oceans are applied to the three large "gulfs" that extend northward between the continents. Because of the topographic relationships the North Polar sea is considered as a part of the Atlantic ocean. Southern or Antarctic ocean is sometimes used to designate the waters of the southern latitudes extending from the antarctic to the subtropical convergence (about 40° S.).

Various systems have been proposed and used for designating subareas of the open ocean. Some of these are based on arbitrarily designated boundaries, others make use of the bottom topography and others are based on climate, currents and physical and biological criteria.

Examination of the globe shows that the proportion of water is much greater in the southern hemisphere than in the northern.

All oceans and seas	361.06×10^6 km.^{2}	70.8%
All land.	148.89×10^6 km.^{2}	29.2%
Northern hemisphere—Oceans and seas .	154.70×10^6 km.^{2}	60.7%
—Land . . .	100.28×10^6 km.^{2}	39.3%
Southern hemisphere—Oceans and seas .	206.36×10^6 km.^{2}	80.9%
—Land . . .	48.61×10^6 km.^{2}	19.1%

Relief of the Sea Floor is important for many reasons. It forms the lower and lateral boundaries of the ocean waters; its elevations impede the free flow of water; it affects the distribution of sediments and is of interest to the geomorphologist and geologist. The development of echo-sounding devices (about 1925) greatly accelerated the study of submarine topography by providing a simple and rapid method of obtaining depth measurements.

The greatest depths occur in the Pacific ocean where soundings of about 10,500 m. have been obtained in the Philippine trench by the "Emden" and more than 10,000 m. in the Japan trench by the U.S.S. "Ramapo." The greatest depth in the Atlantic, 8,750 m., was obtained by the U.S.S. "Milwaukee" in the Puerto Rico trench. The great depths in the Pacific exceed the elevation of Mount Everest by about 1,500 m.

The relative distribution of elevation and depth can be shown by a hypsographic curve, showing two primary levels of reference, one slightly above sea level, the other at depths between 4,000 to 5,000 m. Elevations of more than 1,000 m. on land and depths greater than 6,000 m. represent only a small percentage of the earth's surface. Also, there is only a relatively small percentage of the sea bottom with depth between 200 and 3,000 m. The mean elevation of the land is 840 m. and the mean depth of the oceans is 3,800 m. The hypsographic curve should not be interpreted as an average profile of the land surface and sea bottom because the highest mountains are commonly near the coast line (*e.g.,* west coast of South America) and the greatest depths are found near the margins of the ocean and not in the middle of the oceanic depressions.

The continental shelf, with depths less than 200 m. to 400 m., is of variable width, ranging from about 750 mi. to the north of Norway and the U.S.S.R. to virtually zero off mountainous coasts. It averages about 30 mi. in width. Although the average slope of the shelf is small, detailed surveys reveal minor terraces, ridges, hills and depressions as well as steep-walled canyons, some of which are probably related to erosion and deposition during periods of lowered sea level. The inclination of the continental slope varies between about 2° and 3.5°, being least off low-lying land and steepest off mountainous coasts. Submerged slopes of volcanic islands are similar to the exposed portions and may be as great as 50°.

The *Carte Générale bathymétrique des océans dressée par ordre de S.A.S. le Prince Albert de Monaco,* first issued by Prince Albert of Monaco in 1904 and more recently by the International Hydrographic bureau at Monaco, is the standard representation of oceanic bottom topography. Periodic revisions are made, and the third edition was being issued when interrupted in 1939 by the outbreak of World War II. Smaller and less detailed charts of deep-water topography are published by various national hydrographic agencies.

With the great increase in bathymetric knowledge since 1930, agencies such as the Geological Society of America have sponsored the preparation of detailed charts of the continental shelves and slopes. These have brought to light a complex topography of which the most striking features are submarine canyons which cut into the slope and sometimes across the shelf. Off the Hudson, Congo and Indus rivers are canyons which bear some relation to the rivers. Others occur in areas where there are no large rivers. In general, they are V-shaped in profile, with bottoms sloping continuously outward. Some are winding and many are branched. The larger canyons are comparable in size and relief to the Grand Canyon of the Colorado river. The question as to the origin of these canyons is unsettled.

MARINE SEDIMENTS

Most of the sedimentary rocks on land were dep
the sea. A study of the various marine environment
tion, the associated marine organisms, texture, comp
colour of the sediments is therefore of interest beyo
of oceanography because only in the sea can be found
to many geological problems.

Sir John Murray is credited with the first intensiv
tion of marine sediments, and the report on the "
material (Murray and A. Renard, 1891) set the patte
later investigations. The development of chemical
techniques has opened new fields of study; for exa
spectroscopy has provided a means for identifyi
grained clays which were previously considered to b
material.

Sources of Sedimentary Material.—The materi
the sea floor can be grouped in six general classes,
proportions of each may vary between wide limits:

1. *Terrigenous debris,* arising from mechanical
and chemical decomposition of exposed rocks, is carri

2. *Volcanic debris* is contributed by land volcano
those completely below the sea surface. Volcanic a
for tremendous distances in the air and floating pum
dispersed by currents.

3. *Remains of organisms,* principally the hard calc
tal structures of plants and animals, make up a larg
of many deep-sea sediments and also shallow-wate
tropical seas. Skeletal structures of silica are less
are widely distributed. Both plant and animal rem
portant. These organic remains correspond to the fo

4. *Inorganic precipitates* are never abundant but a
conspicuous and diagnostically important. Example
carbonate (in a few areas), dolomite, iron and mang
phosphatic and barite nodules and, where H_2S is pre
sulphide.

5. *Products of chemical transformation* are min
by the interaction of sea water and rock particles.
glauconite, phosphorite, feldspar, phillipsite and cla

6. *Extra-terrestrial materials* are extremely rar
magnetic spherules and small brown crystalline spher
in red clay are believed to be of meteoritic origin.

Transportation of Sedimentary Material.—M
duced to the sea by erosion, rivers, the air, or pro
sea, may be carried for great distances before it re
resting place. With the exception of ice and orga
is a general rule that small particles, or at least li
will be carried the greatest distances from their point

Ice is important only in the higher latitudes. Gl
heavy load of unsorted rock debris and, when they
sulting icebergs may carry boulders and pebbles as
material thousands of miles before they melt and dr
their burden to the bottom. Sea ice near shore is
solid to the bottom during winter. When it thaws
break away and carry with it the frozen sediment wh
elsewhere as the thawing continues.

Organic rafting does not carry much material but
bergs, rafts of land vegetation or large seaweeds
rocks and pebbles far from land.

Atmospheric transport of volcanic ash distributes
all over the earth. In areas where strong offshor
across arid regions, as off the west coast of Africa,
forms an important constituent of the deep-sea sed

Currents carry material in several different
sinking particles will be carried along as they
toward the bottom. Near and on the bottom, ma
moved by mudflows, sliding, rolling and saltation
carried in suspension. All these processes have thei
in the atmosphere in landslides, drifting sand and
dust storms. There is little direct evidence of mudf
are believed to be common in areas of steep slop

The eroding velocity required to move particles on
ı is not well known, but it is believed that a flow of
centimetres per second will carry particles less than
etre in diameter.

roperties of Marine Sediments.—The over-all char-
of a sediment are colour, texture and composition.
diments vary from white through gray to black, with
f various amounts of yellow, red, blue or combinations
olours. Light-coloured sediments are usually coarse-
Black sediments are typical of stagnant conditions.
s the sediments are often reddish, and most shallow
deposits are green or olive-green. The deep-sea red
dish or brown in colour, and sediments high in skeletal
are generally light-coloured. Texture covers a wide
n boulders and cobbles to those sediments composed
impalpable clay. Most samples contain a range in
es and, except in areas of currents, are not well sorted.
sition is of course an index of the sources of the con-
f a sediment. Microscopic and chemical analyses are
ways of determining the composition.

and Terrigenous Sediments.—Pelagic sediments are
d in deep water far from land. Materials containing
% of organic remains are called red clay. The organic
then divided into calcareous and siliceous oozes which
re than 30% of organic remains. Calcareous oozes
obigerina ooze, in which pelagic foraminiferal remains
nt; (2) pteropod ooze, containing conspicuous shells
nolluscs; and (3) coccolith ooze, containing large num-
letal fragments of Coccolithophoridae. Siliceous oozes
iatom ooze, containing principally diatom frustules;
diolarian ooze, containing abundant skeletons of radio-
rigenous sediments are variable in colour, texture and
, but always contain some recognizable terrigenous
the basis of texture they are designated as cobbles,
d, silt, mud, etc., or combinations of these terms.
ation of composition or origin is indicated by such
lcareous, siliceous, coral, volcanic, glacial, etc., gen-
ked by an adjective describing the colour.

tion of Pelagic Sediments.—Red clay and globi-
are the most abundant types. Diatom oozes are
o high latitudes, and radiolarian oozes are almost
limited to the Pacific, whereas pteropod ooze is signifi-
the Atlantic.

tion of Pelagic Sediments.—There are three ex-
s of pelagic sediments: those completely devoid of
ains (that is, pure red clay), those entirely composed
us remains and those made up of siliceous remains.
ost sediments can be considered as mixtures in varying
of the three extreme types, although sediments high
us remains contain few siliceous skeletons, and vice
great differences in texture, physical and chemical
of the three extreme types are reflected in the prop-
ediment sample. Calcareous sediments usually contain
ial larger than 0.1 mm., but broken and disintegrated
make up most of the sample. The red clays have a
neter of about 0.001 mm. Diatoms and radiolarian
usually larger than 0.1 mm.

analyses of red clay (free from calcium carbonate)
compared to igneous rocks, it is higher in aluminum,
nganese, and lower in calcium, potassium and sodium.
proportion of iron and manganese is believed to be
f deposition of their oxides in the sediments as con-
Nodules containing these oxides are frequent constit-
l clay. The fine material is believed to originate on
some extent, by the submarine weathering of volcanic
he following clay minerals have been found in marine
kaolinite, montmorillonite, hydrated halloysite and a
e clay. Many of these substances are capable of
exchange.

Carbonate Deposition.—Most of the calcareous
of organic origin, but in certain restricted shallow-water areas, such as in the Red sea and on the Bahama banks, direct chemical deposition occurs. Precipitation of calcium carbonate by organisms is favoured by warm temperatures and by the activity of plants which reduce the total CO_2 content of the water and thus increase the $CO_3^{=}$ ion concentration. In the open ocean the deposition of calcium carbonate is affected by (1) solution during settling to the bottom and (2) solution on the bottom. The concentration of calcareous debris will depend on these two factors and, in addition, upon the relative rate of accumulation of inorganic debris. Below 3,000 m. the calcium carbonate content decreases rapidly with depth. In the North Pacific the content is relatively low at all depths. The decrease with depth is believed to be the result of solution during sinking and on the bottom, and the anomalous condition in the North Pacific can probably be explained in terms of these factors. Calcareous remains behave as coarse particles and accumulate on topographic highs, whereas the fine-grained clays are swept into the depressions.

Organic matter forms a small but important constituent of the sediments. The decomposable organic debris settling to the bottom forms the source of food for benthic animals and bacteria; in turn, their activities alter the chemical environment on and in the sediment, and burial of organic debris removes from solution significant quantities of carbon, nitrogen and possibly other elements. Organic-matter content averages about 1% in pelagic sediments and 2.5% in nearshore deposits. High values are found in bays, estuaries, isolated basins, fjords and beneath stagnant waters such as the Black sea. In general, the organic-matter content decreases with depth in the sediment core because of bacterial decomposition. Organic material in fossil sediments is believed to be the source of petroleum.

Rates of sedimentation have been estimated by stratigraphic and supply methods. Core samples up to about three metres long taken in the open ocean of the Atlantic have revealed varying composition with depth. Based on the pelagic foraminiferal remains and on the presence of layers containing coarse terrigenous debris, supposedly ice-borne, it has been possible to establish the thickness of the layer deposited since the last glacial period. The average rates for globigerina ooze, red clay and a terrigenous blue mud are 1.2, 0.86 and 1.78 cm. per 1,000 years, respectively.

Other scattered data indicate rates of deposition of the order of 1.0 cm. per 1,000 years or less for pelagic deposits. Although highly variable, it is believed that nearshore deposits accumulate at an average rate of about 10 cm. per 1,000 years.

Factors Determining Character of Sediments.—The factors most important in determining the character of marine sediment are (1) general topography and depth of the site of deposition, (2) relation of site of deposition to sources of inorganic material, (3) physical and chemical conditions in the water column overlying the site of deposition. Topography is, in one sense, a measure of the action of water movements in transporting material, highs being swept clear of fine debris which finds its way into depressions. The various modes of transportation and proximity of sources of material must also be evaluated. The character of the physical and chemical conditions is the fundamental factor in estimating the contribution of calcareous and siliceous skeletal material and of organic matter.

CHEMISTRY OF SEA WATER

If suspended material of organic and inorganic origin is excluded, sea water is an aqueous solution of dissolved solids and gases. For the more abundant elements the early results of W. Dittmar (1884), based on the "Challenger" material, agree well with the best estimates based on analyses up to 1940.

The table contains a list of all elements known to be present as dissolved compounds excluding gaseous oxygen, nitrogen and the inert gases neon, helium and argon. A total of 49 elements are known from direct or indirect analyses.

Chlorine, present as chloride ion, is the most abundant element and accounts for about 55% of the dissolved solids. Six ions, chloride, sodium (30.6%), sulphate (7.7%), magnesium (3.7%), calcium (1.2%) and potassium (1.1%) together make up more than 99% of the dissolved solids. It will be noted that for the following elements ranges in concentration are indicated: silicon, nitrogen compounds, phosphorus compounds, arsenic, iron, manganese and copper. These are substances which are present in small amounts but which are essential to living organisms. Nitrate, phosphate and silicate are often called fertilizers or plant nutrients.

Dissolved Gases.—All the atmospheric gases are present in solution in sea water. In stagnant areas (no dissolved oxygen) hydrogen sulphide is found and methane may be present.

The solubility of oxygen and nitrogen decreases with increasing temperature and salinity. At saturation, the following values occur in water of $\mathrm{Cl}=19\,^0/_{00}$.

	Oxygen, ml./l.	Nitrogen, ml./l.
0° C.	8.08	14.40
20° C.	5.38	9.65

Although the ratio of oxygen to nitrogen in the atmosphere is 1:3.7, in the sea water it is about 1:1.7 because of the greater solubility of oxygen.

Dissolved nitrogen gas is not affected by biological activity and is always present at about the saturation value determined by the temperature and salinity. At depths greater than a few hundred metres oxygen is generally below saturation because of its utilization. In large areas of the Pacific at mid-depths it is present in amounts less than 1 ml. per litre. In the euphotic zone (less than 100 m.) photosynthetic activity may increase the oxygen content over the saturation value.

*Elements Present in Solution in Sea Water**
(Dissolved gases not included)

Element	mg./kg. $\mathrm{Cl}=19.00\,^0/_{00}$
Chlorine	18,980
Sodium	10,561
Magnesium	1,272
Sulphur	884
Calcium	400
Potassium	380
Bromine	65
Carbon	28
Strontium	13
Boron	4.6
Silicon	0.02 –4.0
Fluorine	1.4
Nitrogen (comp.)	0.01 –0.7
Aluminum	0.5
Rubidium	0.2
Lithium	0.1
Phosphorus	0.001–0.10
Barium	0.05
Iodine	0.05
Arsenic	0.01 –0.02
Iron	0.002–0.02
Manganese	0.001–0.01
Copper	0.001–0.01
Zinc	0.005
Lead	0.004
Selenium	0.004
Caesium	0.002
Uranium	0.0015
Molybdenum	0.0005
Thorium	<0.0005
Cerium	0.0004
Silver	0.0003
Vanadium	0.0003
Lanthanum	0.0003
Yttrium	0.0003
Nickel	0.0001
Scandium	0.00004
Mercury	0.00003
Gold	0.000006
Radium	$0.2–3\times10^{-10}$
Cadmium	..
Chromium	..
Cobalt	..
Tin	..

*From H. U. Sverdrup, M. W. Johnson and R. H. Fleming, *The Oceans* (Prentice-Hall, Inc., 1942).

Carbon dioxide in sea water is chiefly present as carbonate and bicarbonate ions balanced against basic cations. It is present in the following forms, and for any given set of conditions an equilibrium prevails:

CO_2 (dissolved) $\rightleftarrows H_2CO_3 \rightleftarrows HCO_3^-$ (bicarbonate) $\rightleftarrows CO_3^=$ (carbonate). To remove all CO_2, a strong acid must be added to sea water. If CO_2 is removed, the equilibrium is shifted toward more carbonate ion; if CO_2 is added, the amounts of bicarbonate and then carbonic acid and dissolved CO_2 increase. In equilibrium with the atmosphere, the amount of free CO_2 and H_2CO_3 solution decreases with increasing temperature.

The *p*H or hydrogen ion concentration depends u
tent, temperature and salinity, and varies between a
8.4. The higher values occur near the surface and the
in water where the oxygen has been consumed and
CO_2 in respiration.

The alkalinity is a measure of the basic cations ba
weak acids (carbonic and boric). It bears a relati
ratio to the chlorinity and is affected slightly by pre
solution of calcium carbonate.

The solubility of calcium carbonate is not defi
Apparently warm surface sea water is nearly saturat
supersaturated, whereas the deeper waters are u
where much oxygen has been consumed.

Effect of Rivers.—The composition of the disso
river water is variable and depends upon the amou
and type of rocks and soil which have been in con
water. F. W. Clarke (1924) has estimated that riv
add 2.73×10^9 metric tons of dissolved solids to the
carbonate is notably more abundant in river water,
there is a deposition by organisms which probably
tendency to increase the content of calcium. Estima
of the ocean based on the present rate of supply of
rivers lead to values of about 100,000,000 years, a
time than estimates made by other means.

Geochemistry of the Ocean Waters.—The tot
dissolved salts in the sea is about 5×10^{16} metric tons.
form a layer of salts 45 m. thick over the entire ear
thick over the present land area. It is estimated that
of rock have been weathered for every kilogram of
oceans. Sulphur, chlorine, bromine and boron occu
greater than were present in this amount of rock a
sumably present as volatile substances in the primeva
Elements forming relatively soluble compounds, not
sodium, potassium, magnesium, carbon, strontium,
iodine are present in amounts greater than 1% of
supply. Silicon, aluminum and iron which are abun
are present only as minor constituents in sea water
do not form soluble compounds.

Composition of Marine Organisms.—Most of
listed in the table have been found in organisms, s
also contain a few rare elements not yet reported dir
water. It is best to consider the composition of m
in three parts, organic material (soft tissues), skele
and body fluids. The composition of carbohydrat
proteins are relatively uniform in elementary comp
etal structures vary greatly, and the inorganic solute
fluids are only slightly modified sea water. A comp
relative compositions of organisms and the dissolve
sea water shows that the organisms "concentrate"
phosphorus, and sometimes iron and silicon in the
skeletons. Since these elements are scanty they ca
exhausted and, hence, produce desert conditions in th
of plant and animal life because of lack of fertilize
of water.

It has been found that the ratios of carbon:n
phorus in marine organisms and in sea water are virt
41:7.2:1 by weight or 106:16:1 by atoms. T
through photosynthetic activity and their regene
respiratory activity is parallel. Regions low in p
low in nitrogen and when the oxygen content is low
are abundant. The surface layers of the open oce
because of the virtual absence of phosphate and
pounds. Regions where deeper waters are brought
by winter overturn, mixing or upwelling are the v
of the sea, teeming with microscopic plant life, zoop
and marine birds (*see* MARINE BIOLOGY). In higher
temperatures and lack of light limit photosynthe
winter and allow time for the regeneration of the
ments. Estimates of total production can be made
of the depletion of nutrients (*see* below).

Salinity and Chlorinity.—In 1902 an internat

ned the relationships between salinity, chlorinity and
f sea water. Salinity is a defined measure of the total
ids (salt content) of the water. The chlorinity is an
red quantity obtained by titrating sea water with
following a prescribed method. The two are related

$$\text{Salinity}=0.03+1.805\times\text{chlorinity}.$$

are always expressed as grams per kilogram, that is,
usand, for which the symbol $^0/_{00}$ is used.
ation with silver nitrate, bromides and iodides are
with the chlorides but are computed as if they were
ence, the chlorinity is greater than the chloride con-
e changing atomic weights slightly affect this relation-
ause of the difficulty of preparing standard chloride
fficient accuracy, all oceanographic work is based on
r" (*eau de mer normale*) prepared under the auspices
tional commission.
y of the salinity: chlorinity relationship depends on
careful chemical analyses which have shown that,
where the water is collected, the ratios between the
ments are virtually constant. Slight variations are
ur in certain elements affected by biological activity,
of high dilution the concept of constant composition
ecause the ratios of dissolved salts in river water are
different from those in the sea.
the constancy of composition, the density at a given
s related to the salinity and chlorinity; and if one
nown, the others can be obtained from M. Knud-
aphical Tables. Salinity is rarely measured directly
nity titration is the standard method of determining
ion of sea water. Density and certain other physical
also used. Density measurements are made with
ottles, by total immersion hydrometers, or floats.
ductivity and refractive index methods have also
Since density and the other properties depend on
they are always standardized against chlorinity
on control samples.
es in the oceans range from about −2° C. to more
The lowest value is limited by the freezing point of
the upper limit by processes of radiation and ex-
t with the atmosphere. Temperatures higher than
cur in land-locked tropical seas such as the Red sea
n gulf. The range in salinity is generally between
$/_{00}$. The surface salinity in high latitudes, in re-
rainfall and off large rivers, may be much lower,
semienclosed areas, such as the Gulf of Bothnia,
zero. In isolated seas in intermediate latitudes,
d sea, the salinity may exceed $40^0/_{00}$.
tative salinity of $35^0/_{00}$ or a chlorinity of $19^0/_{00}$
is often used in discussions of the composition of

Hydrostatic pressure is expressed in atmospheres or
entimetre-gram-second system. An atmosphere is
3×10^6 dynes/cm². One million dynes per square
s designated as 1 bar by V. Bjerknes. The unit in
n oceanography is the decibar, one-tenth of a bar.
ere corresponds to approximately ten metres of
re, depths in metres and pressures in decibars are
nearly the same numerical value.
nge from zero at the surface, neglecting atmos-
e, to more than 1,000 atmospheres (about 15,000
inch) or 10,000 decibars in the deepest parts of the

Sea Water.—Density is the mass per unit volume
reported as grams per cubic centimetre. The den-
ter depends upon its temperature, salinity and the
ressure. Density is represented by the symbol
scripts indicating the three variables. Since the
water is in the range 1.000 to 1.040, it is common
ort σ_t values where

$$\sigma_t=(\rho_{s,t,p}-1)\ 1{,}000.$$

If the water is at 0° C. and atmospheric pressure, the direct relationship between density, salinity and chlorinity is given by M. Knudsen's *Hydrographical Tables.* At any other temperature the correction for the thermal expansion can be obtained from the same source. The compressibility correction necessary for computing the density *in situ* was derived by Bjerknes and J. W. Sandström.

In oceanographic work the specific volume (α) is often used instead of the density. Because the range in values is small it is convenient to employ specific volume *anomalies* which are indicated as δ where

$$\delta=\alpha_{s,t,p}-\alpha_{35,0,p},$$

the value of $\alpha_{35,0,p}$ being that of water of salinity $35.0^0/_{00}$, temperature of 0° C. at the indicated pressure, p, expressed in decibars. Tables for obtaining δ are given by H. U. Sverdrup, M. W. Johnson and R. H. Fleming.

PHYSICAL PROPERTIES OF SEA WATER

The properties of pure water are dependent upon temperature and pressure; those of sea water are also affected by the salinity. Details concerning the physical properties can be found in the International Critical Tables and are stated by N. E. Dorsey, and by Sverdrup *et al.* Earlier compilations are given by O. Krümmel.

Heavy water (deuterium oxide) is present in sea water in amounts greater than in fresh water or rain water. The ratio of hydrogen to deuterium is about 7,000:1.

Thermal expansion increases with temperature, pressure and salinity.

Thermal conductivity is essentially the same as for pure water. The molecular transfer of heat, however, is rarely a significant process in the sea, where the state of motion results in eddy conductivity which is many times greater.

Specific heat at constant pressure decreases slightly with increasing salinity, temperature and pressure.

Latent heat, the amount of heat required to produce one gram of water vapour at the same temperature as the water, decreases with increasing temperature. Between 0° and 30° C., latent heat in calories $=596-0.52\times t°$ C.

Adiabatic temperature changes must be taken into account in studying the temperature distribution in the deep basins. Compression results in heating, expansion or pressure release in cooling. Although the effect is small, water raised from 10,000 m. will cool more than 1° C. when brought to the surface. The adiabatic gradient is approximately 0.1° C. per 1,000 m.

Colligative properties, vapour-pressure lowering, freezing-point depression and osmotic pressure depend upon the salinity. The effects of temperature on all of these properties is believed to follow the usual relationships for solutions.

Maximum density of pure water is at nearly 4° C. For sea water the temperature of maximum density decreases with increasing salinity. For salinities greater than about $25^0/_{00}$ the temperature of maximum density is below the freezing point; hence, the water continues to cool and mix until freezing occurs at the surface.

Compressibility must be known to compute density *in situ.* It decreases with increasing temperature, salinity and pressure.

Viscosity and diffusion, like thermal conductivity, have little effect on the transfer of momentum and of chemical properties because of the dominant role of turbulent transfer. Eddy coefficients much greater than the laboratory values, but highly variable, are found in the sea.

Surface tension decreases with increasing temperature and increases slightly with salinity. Organic substances in solution often reduce the values below those for "pure" sea water.

Refractive index has been used as an indirect method for measuring the salinity. It increases with salinity and decreases with increasing temperature.

Electrical conductivity has also been used for an indirect method of determining salinity. The conductivity increases with salinity and temperature.

Velocity of sound in sea water increases with increasing temperature, salinity and pressure, with extreme range of values between about 1,450 and 1,550 m. per second. Water is a good conductor of sound, absorption losses being negligible except at supersonic frequencies. Echo-sounding systems are based on timing the interval required for a sound impulse to travel from the ship to the sea bottom and for the echo to return to the ship. Horizontal transmission of sound is used in surveying work (radioacoustic-ranging).

Absorption of radiation (transparency and colour). The penetration of light in the sea is important not only in heating the water but also to the photosynthetic activity of plants and to the vision of animals. Pure water is most transparent to radiation in the blue and green portions of the spectrum; thus, sunlight transmitted through clear water appears blue. Studies of sea water indicate values approaching those of pure water but in many areas, particularly near shore, the transparency is much reduced and there is a shift in the colour of the transmitted light toward the green and yellow.

The reduced transparency in the sea is believed to be caused by minute particles of dust and organic debris that scatter the light. In coastal waters organic debris and a dissolved yellow substance, probably of organic origin, contribute greatly to the reduced transparency.

Water is virtually opaque to ultra-violet and infra-red radiation. Approximately 50% of the sun's radiation is in the long-wave, infra-red region and is absorbed in the first few centimetres of water.

The transparency of sea water has been studied by means of the Secchi disk, by spectrophotometers and by photoelectric cells with filters which are lowered in the sea. Photographic plates exposed at depths as great as 1,000 m. have shown some fogging, but the amount of light present below 500 m. in clear tropical latitudes is probably inadequate for vision. In coastal waters this limit of visibility may be as shallow as 50 m.

The colour of the sea ranges from a deep blue in areas of clear water such as the Sargasso sea and the Mediterranean to blue-green and green, and a greenish-brown near shore. The colour of the water is usually recorded on the "Forel scale," which is an arbitrary series of colours ranging from blue to yellow. The blue colour is attributed to the scattering of light by extremely minute particles and possibly by molecules so that it is comparable in origin to the blue of the sky. Near shore the green and yellow are associated with plankton, organic and inorganic debris and yellow pigment. The sea surface is sometimes discoloured by concentrations of debris or living organisms. "Red water" is common in certain areas where tremendous concentrations of algae or dinoflagellates occur. The Red sea and the Vermilion sea (Gulf of California) are named for such phenomena.

ICE IN THE OCEAN

Ice in the ocean occurs as icebergs or as sea ice. Icebergs are formed by the "calving" of glaciers and consist therefore of pure ice. Sea ice is ice that forms when sea water freezes and generally contains salt. There is an elaborate terminology to describe icebergs and sea ice.

When sea water is cooled to its freezing point, which lies below that of fresh water, elongated crystals of pure ice are first formed. These grow rapidly into a matrix in which sea water becomes trapped in amounts which depend upon the rate of freezing. Sea ice therefore consists of pure ice full of small cells that contain brine. When the temperature of the ice decreases, the cells decrease in size and the brine becomes more concentrated. On the other hand, when the temperature of the ice rises, the cells increase in size and the brine becomes diluted. When the temperature of the ice approaches the freezing point of pure ice (0° C.), the ice becomes honeycombed and the brine trickles down, leaving the upper layers free from salt. Thus, at the end of the summer the tops of hummocked arctic ice consist of pure ice which on melting renders potable water.

The physical properties of sea ice depend upon the salt content of the ice and upon the presence of air bubbles.

OCEANOGRAPHIC METHODS

Oceanographic studies fall into two general groups, servations which must be made *in situ,* and those that c on collected samples which, once obtained, can be exa later time either on shipboard or in the laboratory. group of observations are soundings, observations of w ments (currents, waves and tides), temperature, transp certain other physical properties. In the second group of the chemical and physical properties of the water, e of biological collections and marine sediments, which always based on a laboratory examination of the sampl specialized devices are necessary for making observatio lecting samples from below the sea surface.

Soundings in deep water are obtained by paying out multistrand wire with a weight attached to the end. weight strikes the bottom, the tension on the wire is r the amount of wire paid out is read off on a "me Depths greater than 10,000 m. have been measured i The introduction of sonic-sounding (echo-sounding) simplified this phase of the investigations.

Subsurface temperatures are usually measured by reversing thermometers, first developed about 1878. special mercury-in-glass instruments enclosed in a sheath to protect them from pressure. These devices w temperatures with an accuracy of ±0.02° C. and can the greatest depths. They are usually attached to sampling bottles and lowered on a heavier wire rope used for sounding. Reversing thermometers, althoug accurate, do not provide detailed information on the tribution of temperature. To obtain such information temperature recorders, such as the bathythermograph devised, which can be lowered from a vessel under way record temperature against depth in the upper 300 m.

Water samples for salinity determination and for p chemical examination are obtained by special meta which usually have the thermometers attached to the more of these bottles are attached to the wire rope a while open. At the required depth a messenger is dro the wire which activates a mechanism closing the first releasing another messenger which closes the second so on. When all bottles have closed, they are raised face and emptied into special glass bottles for later stu

Bottom samples are collected by means of snapp tubes and dredges, and for work in deep water these massive and require heavy gear for lowering and ra Snapper samplers are built like clam shells and scoop of the superficial layers of the sediment. Coring tube into the sediment by heavy weights or by an explo which is detonated when the device strikes the bottom to about 10 m. in length have been collected in depths 4,000 m. Snappers and coring tubes can be used only soft sediments. To collect samples of rock it is neces drag buckets or strengthened types of dredges simil used in biological collecting. Methods used to collect animals are described elsewhere (*see* MARINE BIOLOGY

TEMPERATURE AND SALINITY

Heating, Cooling and Evaporation.—The surfa the oceans receive heat by absorption of radiation fr and the sky and lose heat by back radiation, by condu atmosphere and by evaporation. Heat is also transpo out of any region by currents. The temperature in a depends, therefore, in a complicated manner upon the circulation of the atmosphere and the currents. Altho amount of heat is conducted through the ocean botto interior of the earth, its effect on temperature dis masked by features related to the circulation of the w

Evaporation takes place when the vapour pressure surface is greater than that in the air, and this condi exists when the sea surface is warmer than the air. T contrasts between air and sea temperatures are found i the eastern coasts of the Asiatic and North American lar continental air flows out over the warm waters of y currents, the Kuroshio and the Gulf stream. There- the largest evaporation takes place off the eastern nter. Simultaneously, the air is heated and will west coasts of the continents as moist and warm air. unction as a huge system of circulating warm water; yers are heated in summer, and the warm waters are along the east coasts of the continents where in ive off part of their heat content to the air and supply re with moisture.

ure and Salinity of the Sea Surface.—Merchant ent nations have collected from the oceans so many of sea-surface temperatures that it has been possible arts showing the average annual temperature of the s well as mean monthly temperatures.

arge tropical areas of the oceans the average sea- erature is above 25° C., exceeding 27° in the Atlantic ° in the Pacific and Indian oceans. According to Otto e percentage areas of the different oceans of high erature are as follows:

Percentage of Ocean Surface

erature	Atlantic	Indian	Pacific
(25° C.)	22.4	38.0	40.1
(20° C.)	50.1	51.7	58.4

ntic and Pacific oceans these warm areas are narrow n parts of the seas and wide in the western parts, lian ocean this feature is reversed. To the north and warm region the sea-surface temperature decreases erms tend to run east-west. There are many excep- ule, however, particularly in the eastern parts of the Pacific oceans where the currents exercise a great n the course of the isotherms.

variation of the sea-surface temperature is small in here the annual range is only 1°–2° C. In the south- e annual range reaches a maximum of 5°–6° C. in S. and decreases again to about 2° C. in the antarctic e North Pacific and the North Atlantic oceans the al range reaches about 9° C. in lat. 40° N. and de- small value when approaching the arctic. In the ns the east-west variation in annual range is more han the north-south. Thus, in lat. 40° N. the annual ace temperature is about 17° C. on the east coast of pared with 4° C. on the American west coast. This ntrasts are related to the character of ocean currents.

al range of the sea-surface temperature is small In the tropics the range is from 0.2° to 0.3° C. and tudes in summer it is about 0.4° C. The range de- e altitude of the sun at noon, the cloud cover and the . It increases with increasing noon altitude of the eases with increasing cloudiness and wind.

y of the surface water is less well known because the of the salinity is more difficult than the measure- ea-surface temperature. Most of the available data from analysis of water samples collected by merchant are sufficient for the construction of charts showing ity but the seasonal variation in salinity can be exam- d areas only.

the oceans the average sea-surface salinity in any cording to Georg Wüst, equal to a basic value plus a epends upon the difference between evaporation and

$$S=S_0+k(E-P)$$

e average surface salinity, S_0 the basic value, E the (in centimetres), P, precipitation (in centimetres) stant. The constant k is the same for all oceans, but inity value differs from ocean to ocean. For the ans, the South Atlantic and the South Pacific, the milar, $34.50^0/_{00}$ (parts per thousand) and $34.64^0/_{00}$, but for the North Atlantic the basic value is for the North Pacific it is $33.7^0/_{00}$. The Indian t been examined. The higher value for the Atlantic is probably related to the outflow of high-salinity water from the Mediterranean.

According to the above formula, a high surface salinity is found where evaporation greatly exceeds precipitation, and a low surface salinity is encountered where precipitation exceeds evaporation. Thus, belts of maximum salinity are found in both hemispheres in latitudes 20° to 25° where precipitation is small. The extremes are about $37.5^0/_{00}$ in the North Atlantic, $37.0^0/_{00}$ in the South Atlantic, $35.5^0/_{00}$ in the North Pacific and $36.5^0/_{00}$ in the South Pacific and Indian oceans. The belts are separated from each other by an equatorial region of lower salinity, 34.0 to $35.0^0/_{00}$, corresponding to the equatorial rain belt, and poleward salinities lower than $34.0^0/_{00}$ are found, corresponding to decreased evaporation and increased precipitation.

Only the major features of the salinity distribution are governed by this simple relationship. Details are related to the currents and, near land, are influenced by outflow of river water. In enclosed seas into which rivers empty, like the Black sea or the Baltic, low surface salinities are found, but in arid regions the salinity of an enclosed sea may be high. Thus, in the Red sea the salinity may exceed $41^0/_{00}$.

In the open ocean the seasonal variation of salinity appears to be small, but in coastal areas large variations occur associated with changes in discharge of river water and changes in currents.

Subsurface Temperature and Salinity.—Processes of mixing tend to produce a surface layer of nearly uniform temperature and salinity. In the tropics the intensity of mixing is nearly the same throughout the year, but in higher latitudes it is much more intense in winter than in summer. In winter it reaches to a depth of 100 to 300 m., and serves to return plant nutrients, phosphates and nitrates to the upper layers. Below the depth to which the winter mixing reaches, there is generally a layer, within which the temperature decreases rapidly with depth, which is called the main thermocline. This layer is not horizontal but is inclined, depending upon the currents. In the northern hemisphere it drops to the right relative to an observer with his back to the current. In summer the mixing penetrates to shallower depths only, depending upon the force of the prevailing wind and other factors. Below the depth to which the summer mixing reaches, is found a seasonal thermocline which in any given locality varies greatly in sharpness and depth.

Below the main thermocline, or roughly below a depth of 300 m., the temperature and salinity in any locality remain constant throughout the year except for such fluctuations as are related to fluctuations in currents. Temperature and salinity vary both horizontally and vertically, however, and these variations are closely related to the character of the oceanic circulation, as described later on.

In an examination of subsurface temperatures and salinities two useful tools have been introduced. B. Helland-Hansen showed that, when in a given region the temperature is plotted against the salinity, the observed values fall on a curve which defines a characteristic temperature-salinity relationship. On the basis of an analysis of such temperature-salinity relationships it has been possible to show that within each ocean characteristic water masses exist comparable to the air masses, which are discussed when dealing with the atmosphere. These relationships have been useful in studying the origin, depths of spreading and modifications of the water masses.

In each ocean there exist water masses which appear embedded between waters of different characteristics and which, with increasing distance from their region of origin, become mixed with the surrounding waters and lose their identity. Thus, the water which flows out from the Mediterranean along the bottom of the Straits of Gibraltar has a high salinity, and between latitudes 50° N. and 40° S. can be traced over the entire eastern North and South Atlantic by means of a salinity maximum at depths varying from 1,000 to 2,000 m. Similarly, low-salinity water sinks in the Antarctic in about lat. 50° S. and spreads to the north, where in the Atlantic ocean it can be traced to 20° N., and in the Indian and Pacific oceans to about 10° S. For tracing the spreading of such special masses, Wüst developed "the core method," the principle of which is to follow maxima or minima of temperature and salinity which are found near the centre, or core, of the water mass. The two methods, together with an examination of the oxygen content, have greatly clarified our concepts of the deep-water circulation of the oceans.

Basins.—Large bodies of ocean water, such as the waters of the Mediterranean, the Black sea, and the Red sea, are enclosed in basins which are in communication with the open oceans through narrow and shallow straits. In other instances the openings to the open ocean may be wide and fairly deep, but the sill depth in the openings may still be small compared with the depths on either side. Examples of such basins are found in the Caribbean sea, the Gulf of Mexico and between the islands of the East Indian archipelago.

Basins can be divided into two types, depending upon the manner in which exchange of water with the ocean takes place. In one type, water flows in along the surface of the openings and out along the bottom, and in the other type the outflow takes place at the surface and the inflow along the bottom. In all cases the water in the basin will be uniform, but in the first type the basin water is formed by sinking of surface water in the basin itself, and its character depends upon the particular climatological conditions of the region. This, for instance, is the case in the Mediterranean and in the Red sea, where basin waters have a high salinity and a temperature corresponding to the lowest winter temperature in the area, in the Mediterranean a salinity of $38.6^{0}/_{00}$ and a temperature slightly above 13°, in the Red sea a salinity of about $40^{0}/_{00}$ and a temperature of about 20°. In the other type, the basin water has the character of the oceanic water that flows in over the sill, but the exchange is often so slow that the water in the basin is practically stagnant. This is the case in the Black sea where water diluted by run-off flows out along the surface of the Bosporus and where Mediterranean water flows in along the bottom, mixes with the outflowing water and reaches the Black sea with a salinity of about $22^{0}/_{00}$ and a temperature of 8°–9° C. In the Black sea this water is stagnant so that instead of containing oxygen it contains large quantities of hydrogen sulphide. Similar basin conditions are found in a number of fjords.

Where many wide openings exist, the surface water often flows freely through several openings, and the character of the water in the basin is determined by that of the oceanic water at the greatest sill depth. In these instances the renewal of the basin water is more rapid, and stagnating conditions are not encountered. In several of these basins the salinity of the basin water is uniform, but the temperature increases toward the bottom, corresponding to the effect of adiabatic processes. Thus, in the Mindanao trench the salinity below a depth of 3,500 m. remains constant at $34.67^{0}/_{00}$, but the temperature increases from 1.58° at 3,500 m. to 2.48° at 10,000 m., corresponding nearly to the increase which would result if water of a temperature of 1.58° were lowered adiabatically from a depth of 3,500 m. (a pressure of about 350 atmospheres) to a depth of 10,000 m. (a pressure of about 1,000 atmospheres).

OCEAN CURRENTS

Relation between Currents and Distribution of Temperature and Salinity.—The existence of large-scale permanent ocean currents is related to the fact that the sea surface is not flat but in many areas is inclined relative to the true horizon. Where the sea surface is inclined, the water tends to run downhill; but the effect of the earth's rotation enters so that the current runs, instead, parallel to the height contours of the sloping sea surface. It is well known that the wind does not blow from regions of high pressure to regions of low pressure, but that in the northern hemisphere, an observer with his back to the wind has the high pressure on his right and the low pressure on his left. This experience is explained by stating that the wind blows in such a manner that the pressure gradient is balanced by the deflecting force of the earth's rotation (the Coriolis force) which is directed at right angles to the motion, in the northern hemisphere to the right and in the southern hemisphere to the left. Similarly, an observer facing in the direction in which a current flows has, in the northern hemisphere, the sea surface rising on his right and dropping and the component of gravity acting along the sloping is balanced by the Coriolis force. The slope of the however, is small. Off Cape Hatteras, where the Gulf toward the northeast with a speed of up to 3 knots, the rises to the southeast with a slope of 1.5:100,000. Th about 1 ft. in 11 nautical miles.

Observations show that the permanent currents depths of several hundred metres, but their speed de depth. The existence of these currents demonstrat gentle slopes of the sea surface are also permane which are related to the distribution of density. At the density of the water is nearly uniform and, since are weak, the pressure is nearly constant in any le The heights of the water columns which exert th pressure depend, however, on the average density o Where the average density is low, the water column where it is high, the water column is short. Conse free surface of the sea must slope down from reg density to regions of high density or, since low density equivalent to high temperature and high density is e low temperature, it can also be stated that the sea su down from warm regions to cold regions. Since a c along the contour lines of the sloping sea surface, simple rule that a current flows in such a direction northern hemisphere the warm water is on the right on the left of an observer looking downstream. W mixed layer exists, the rule indicates that the depth thermocline increases to the right.

With this rule in mind, the general relationship b perature distribution and currents is readily recogn the Gulf stream off the North American east coast h waters of the Sargasso sea on the right and the waters on the left. The branch of the Gulf strear along the west coast of Norway has the warm waters the coastal side, and the cold waters of the Norwegia left, and the south-flowing California current has the on the left, in this case on the coastal side.

Computation of Ocean Currents.—Ships' obser rendered information as to the surface currents, ar surface currents have been prepared by the hydrogr of different nations. Few direct observations of sub rents are available, and our knowledge of these is r on computations, using the above stated relationship distribution of density and the currents. Numero observations of temperature and salinity have been which the density at different depths can be found. density, it is possible to compute the slope of the o and of any other surface of constant pressure, relative of a selected pressure surface. Using the rule that conditions exist, the component of gravity acting alo pressure surface must be balanced by the Corioli currents can be computed relative to the unknown c selected standard surface. If it can be shown that a the currents are weak, the computation renders the t

This method was first proposed by H. Mohn ar further developed by B. Helland-Hansen on the bas vestigations by V. Bjerknes. The computations are out by means of convenient tables and have given a plete picture of the currents above a depth of about greater depths the currents are so weak that conclusi direction of flow have to be based upon special fea distribution of temperature and salinity.

Ocean Currents and Winds.—The relation betw currents and the distribution of temperature and sali described above, but nothing has been stated as to t which the currents are maintained. Turning to that find that the oceanic circulation can conveniently b as composed of two systems: (1) a system of fairly r which are mainly confined to the upper 1,000 m. or maintained by the prevailing winds, and (2) a system sluggish currents which reach to the ocean bottom ar water that, in the enclosed seas of lower latitudes, high density by evaporation, and in high latitudes by freezing of ice.

ling winds exercise a twofold influence upon the ion. In the first place they maintain shallow wind in the second place they maintain the distribution of ich the major currents are related. The nature of a rent was first examined by V. W. Ekman, following y F. Nansen, and was later studied by C. G. Rossby. s have been developed on the assumption that the associated with the motion is at each depth balanced l force. The theoretical conclusion is that at the sea urrent is directed about 45° from the wind, to the orthern hemisphere and to the left in the southern. ng depth the direction of the current turns right e velocity decreases until at a depth of 50–100 m. is opposite to that at the surface and the velocity is fraction of the surface velocity. These conclusions ain been substantiated by observations.

nsport of water by a pure wind current is directed s to the wind, to the right in the northern and to southern hemispheres. This transport leads to the ct of the permanent winds. Wind currents produced manent anticyclonic winds of the subtropics will tend he warm surface waters toward the centre of the Thus, they maintain an accumulation of warm water region of high atmospheric pressure and as a result ce slopes down in all directions from that region. an exist as a permanent feature only in the presence ents which roughly run in the direction of the pre- Similarly, where the wind blows along a coast, on the right-hand side, the pure wind current will n surface waters against the coast and a current nning parallel to the coast in the direction of the the coast is to the left, the warm surface waters to sea and are replaced on the coast by cold water om depths of a few hundred metres. This process, wn as upwelling, occurs characteristically on the ornia (spring and summer), Peru and northwest Africa (all year), as well as in other localities periods. In these cases cold water is present along again a permanent current develops running par- st and in the direction of the wind.

receding it follows that the permanent ocean cur- tained by the prevailing winds and tend to flow in f the wind. The currents therefore reflect the cir- e atmosphere but with such modifications as arise s of the coast lines. The broad equatorial currents west are maintained by the steady trade winds. he rules which were stated, the depth of the main ust, in the trade wind regions, increase with in- ce from the equator and, consequently, near the of relatively low temperature must be found at . The presence of this water is related to the direc- rents and is not an evidence of ascending motion, ed.

the eastern shore of the continents the waters of currents must bend north or south. The swift, arm currents along these shores, the Gulf stream, the Brazil current and the Agulhas stream (off ca) are therefore not maintained by the local winds de winds. When these currents turn seaward in s, the bulk of the waters is soon deflected equator- urrents off the western coasts of the continent are d cold (the Canary current, the California current, boldt) current and the Benguela current). Where permit circulation in higher latitudes, the contrast n and western coasts is reversed. Thus, in the the cold East Greenland current flows south off eenland whereas a warm branch of the Gulf stream orth off the west coast of Norway.

ial counter currents, which, in the calm belts, flow to the east as swift and narrow currents embedded between the equatorial currents, are also maintained by the winds but in a more complicated manner. The drag of the trade winds blowing to the west is not completely compensated for by the transport related to wind currents, but the drag also pulls the warm surface waters toward the eastern coasts of the continents. Consequently, sea level is a little higher off the eastern than off the western coasts, the difference in elevation being about 14 cm. in the Atlantic and about 60 cm. in the Pacific ocean, according to oceanographic observations. The equatorial currents, therefore, flow slightly uphill. In the belt of calms or variable winds between the two trade-wind regions there is no drag toward the west which can maintain the up-slope. There the water flows down the sloping surface toward the east, the calm belt lying so close to the equator that the effect of the earth's rotation in deflecting the currents is small. In the Atlantic and Pacific oceans the counter currents are found in 5°–10° N. and vary in intensity with the seasons, but in the Indian ocean the corresponding current is found in 5°–10° S. only during the season of the northwest monsoon which reaches peak intensity in February–March.

Deep-Water Circulation of the Oceans.—The ocean waters are in stable stratification; that is, the density increases with depth and the deep basins of the oceans are filled by water of a density greater than that at the surface. The difference in density between surface and deep water is particularly conspicuous in the tropics where the surface waters are relatively light because of their high temperature. Wherever the density of surface water is increased by cooling or evaporation so that it becomes greater than that of the surroundings, the water sinks and spreads horizontally when it reaches a layer of the density which it had upon leaving the surface. When surface water sinks, it is replaced by water which rises from some greater depth, and this process is called convection. The depth to which convection extends depends upon the manner in which density increases with depth.

In the tropics, cooling never takes place, and evaporation is not intense enough to increase the salinity to such an extent that water of high density is formed in the open sea. The convection processes in the tropics are therefore limited to a shallow surface layer. In middle latitudes the convection reaches deeper in winter, but only in such enclosed seas as the Mediterranean and the Red sea, where evaporation is great, do they penetrate to great depths. In high latitudes, on the other hand, where excessive winter cooling takes place, the convection processes may reach to the bottom of the ocean.

In the North Atlantic, regions of deep convection are found between Iceland and Greenland and in the Labrador sea, where the North Atlantic water, of a salinity close to 35‰, is cooled during the winter. When this water is cooled to between 2.5°–3° C., it attains the same density as the bottom water, and convection can reach from the surface to the greatest depth. On an average for the whole year, about 4,000,000 tons sink every second and spread as a slow deep-water current toward the south. In sections showing vertical distributions of temperature, salinity and oxygen content, this water can be traced by its high salinity, about 34.9‰, its temperature of about 3° C. and its high oxygen content. It fills all the deep basins of the North Atlantic and continues into the South Atlantic at depths between 2,500 and 3,500 m. as far south as lat. 40° S., where it gradually loses its identity because of mixing with water of antarctic origin. In the upper layers of this water mass the temperature and salinity are increased by addition of water from the Mediterranean. The Mediterranean has the character of a large evaporation basin which, below the sill depth of the Strait of Gibraltar, is filled by water of a uniform temperature of about 13° and a salinity of about 38.6‰. This warm and saline water flows out along the bottom of the Strait of Gibraltar, sinks, spreads and mixes with other water masses over large parts of the North Atlantic at depths between 1,000 and 2,000 m. Some water of Mediterranean origin is carried into the South Atlantic, where it can be traced to the latitude of the Cape of Good Hope. The high salinities and high temperatures at moderate depths in the North Atlantic were previously taken as evidence that high-salinity water was sinking in about lat. 30° N., but this concept can not be upheld.

Sinking of surface waters also takes place around the Antarctic continent. There the salinity of the surface water is generally low, but on the shelf surrounding the continent the salinity is greatly increased in winter by the freezing of ice, and water of a temperature of −1.9° C. and a salinity of 34.6‰ is formed and sinks. During sinking it becomes slightly mixed with water of somewhat higher temperature and salinity and reaches the bottom with a temperature of −0.4° C. and a salinity of 34.65‰. Thus, this water has a lower salinity than the bottom water of the North Atlantic, but it has also a lower temperature and is therefore slightly denser. It spreads toward the north, and in the Atlantic ocean it can be traced to about 10° N. lat.

Characteristic of the Antarctic is also a convergence of the surface currents, which can be followed all around the continent between latitudes 50° and 60° S. Surface water of salinity 33.8‰ sinks at this convergence and spreads to the north at depths between 600 m. and 1,000 m. Although the salinity of this Antarctic intermediate water increases by mixing as the water spreads toward the north, a salinity minimum can be traced to 30° N. lat. Part of the intermediate water mixes with the underlying water of North Atlantic origin and is carried back again to high southerly latitudes where it rises toward the surface.

The deep-water circulation of the Indian ocean is simpler because the only major source of deep water is found in the south. The Antarctic bottom water and the Antarctic intermediate water can both be recognized, and between them is found a large water mass which contains components of North Atlantic and Antarctic origins. This water moves to the south at depths between 2,000 m. and 3,000 m. and rises to the surface in the Antarctic.

In the northern part of the Indian ocean, conditions are complicated by the spreading of high-salinity water which flows out from the Red sea along the bottom of the Strait of Bab-el-Mandeb. The amount of Red sea water which enters the Indian ocean, however, is much smaller than the amount of Mediterranean water flowing into the Atlantic and the effect upon distribution of temperature and salinity is correspondingly less.

In the North Pacific ocean no region is found comparable to the regions in the North Atlantic where bottom water is formed. To the north of lat. 45° N. the salinity of the surface waters of the Pacific is generally so low, less than 32‰, that, in spite of winter cooling, the density of the surface water never increases enough to develop deep convection. An appreciable deep-water circulation is therefore confined to the region of the South Pacific where, again, the Antarctic bottom water and intermediate water flow north. These waters are mixed with the great bulk of deep water which contains components of Atlantic and Antarctic origins which have passed to the south of the Cape of Good Hope and to the south of Australia and New Zealand. A return flow to the south takes place between depths of 2,000 m. and 3,000 m.

In the North Pacific the deep water is exceedingly uniform and the circulation sluggish, as evidenced by the low oxygen content of the water. Below a depth of 2,000 m. the salinity varies between 34.65–34.7‰ and the temperature between 2° C. and 1.5° C. A slight renewal of deep water probably takes place by exchange with the South Pacific, deep water moving slowly north in the western Pacific and south in the eastern Pacific. This motion is superimposed upon a general clockwise circulation which extends from the surface to the bottom but is slow below a depth of a few hundred metres.

Relation between Oceanic Circulation and Organic Productivity.—Around the Antarctic continent we find not only sinking of surface water but we also find that large volumes of deep water are drawn to the surface. These bring with them relatively high concentration of phosphates, nitrates and other plant nutrients, and the antarctic waters can therefore support a large amount of marine life. The waters are among the most productive of ocean areas, as evidenced by the large whaling industry which has developed in the antarctic since the turn of the century.

In general, regions of high productivity are found wherever an over-
turn of the surface layers takes place, regardless of the
which brings about such an overturn. In parts of the Nort
vertical convection reaches in winter to the bottom, and by t
overturn the surface waters are well supplied with nutrients
summer when light conditions are favourable, can support
populations of diatoms and other minute marine plants.
regions of the North Atlantic and over large parts of the Nor
the winter convection reaches to depths of a few hundred m
but the mixing caused by this convection is sufficient to rest
surface layers large amounts of plant nutrients and thus
sible a high productivity during summer. Upwelling (p. 6
similar effect, and the regions of upwelling off the coasts of
Peru, Chile and southwest Africa, are also regions of high pr

The deep water of all oceans contains relatively large a
plant nutrients (see *Chemistry of Sea Water*, above). In
Atlantic, the concentrations of these are lower than in any ot

BIOLOGICAL OCEANOGRAPHY

The marine plants and animals should be thought of as
the sea, even as the salts are a part of the sea. They are
bound to its physical processes and are in themselves the ac
chemical changes that involve alternating phases of the mine
organic state of certain salts and gases so vital to biologica
and geological oceanography.

Historically, the early biological studies of the sea were
and mainly descriptive. They were concerned largely with
atic cataloguing of the different kinds of organisms found
This is still the natural procedure in the investigation of
The exploratory-descriptive phase is exemplified especially b
"Challenger" expedition of 1873–76 and by various expedit
U.S. fish commission steamer "Albatross" from 1883 to 192
scriptive phase, though far from complete for the oceans as
in many regions drawing to a close and, especially since the
of the 20th century, has given way to a second phase which
analytical. The analytical phase is concerned particularly w
tors that are important in governing the biological economy
Some of these factors will be brought out in the course of

The sea is the world's largest biological environment. Th
living space that it provides is about 300 times greater than
combined terrestrial and fresh-water environments. This
only from its vast horizontal expanse (71% of the earth's su
especially from the great vertical range from the surfac
depths.

For convenience of study the marine environment is di
two major divisions, namely, the benthic, comprising all of
from high-tide level to abyssal depths, and the pelagic,
all of the water covering the bottom. The benthic divis
divided into the littoral system and the deep-sea system
dividing line arbitrarily set at the 200-m. depth contour.
part of the littoral system to a depth of about 40 to 50
eulittoral. Its greatest depth corresponds to the lower limit
of the more abundant attached plants.

The population of the entire environment is divided into t
ecological groups: (1) the benthos, which includes all orga
as seaweeds, barnacles, clams, crabs, etc., that live on the bot
attached, burrowing or creeping; (2) the nekton, consist
strong-swimming animals such as fishes, whales, etc., of
division; (3) the plankton, which includes floating plants a
that possess little or no effective swimming power and ar
carried more or less helplessly by the water currents. The
forms are constantly in danger of sinking to unfavourable

The plankton is divided into two main divisions: (a) phyt
comprising the microscopic floating plants of which the most
are, first, the diatoms and, second, the holophytic dinoflag
latter being a borderline group between plants and animals
plankton, which comprises a multitude of floating or feebly
animals, mostly microscopic to a few millimetres in size.

From the standpoint of the economy of the sea, the phyt
and the zooplankton are the fundamental groups upon which
sea life is dependent either directly or indirectly. This re
the fact that the floating diatoms and dinoflagellates are
synthesizers of primary food, while the animals that ma
zooplankton are the chief grazers utilizing this plant crop
verting it into animal substance for the use of carnivorou
For this reason, investigations of the oceans have been concer
with the ecological factors, physical, chemical and biological,
or control the production and utilization of these two fu
groups. All biological groups must, however, be carefully in
for only thus can we hope to understand the essential int
ships of the groups and to evaluate the part played by e
various phenomena of the sea. (*See* MARINE BIOLOGY for oth

**Factors of Phytoplankton Production (Organic
tion).**—Phytoplankton growth is dependent upon a numbe
or less clearly defined interacting variable factors, one o
which may be critical to production. The factors of prod
either primary or secondary. The primary or direct factors
concerned with the energy supply, food supply and rate of m
They are light, nutrients, temperature and salinity, and c

proliferation of the individual plant cell. Any one of
at the moment, is not optimal in relation to other fac-
ater is a limiting factor. Thus, light is always a limiting
intensities. The secondary factors control the density of
n, as discussed later.

radiant energy of the sun, is intercepted by the plant
l used in their manufacture of carbon compounds from
le and water. In simple form, this is expressed by the
$O_2+6H_2O=C_6H_{12}O_6+6O_2$. In this endothermic reaction
organic substance of the plant contains more energy than
n the reactants CO_2 and H_2O. This extra energy derived
is stored in the complex plant substance, later to become
chemical energy for life processes of the plant and also,
directly, for that of all animals and heterotrophic bacteria.
n set free in the process of carbon assimilation is used in
lant, but the excess oxygen is an important source for the
e upper layers of the sea. A 5-day period of lively diatom
for example, increase the oxygen content of the water by
.2 ml. per litre. Oxygenation by phytoplankton therefore
r-reaching biological and chemical implications and has
into account also when studying the "age" or source of
because the oxygen content is an index of past conditions.
pper water layer, to depths of 80 m. or less, has sufficient
process of photosynthesis. This layer is known as the
e and varies greatly in depth depending upon latitude,
l season. The depth at which the light intensity is just
bring about a balance between oxygen production and
mption during the process of photosynthesis is known as
tion depth. It is the maximum depth at which the light
fficient for the plants to survive but not enough for crop
has been concluded by British investigators that for
s of the latitude of Loch Streven, Scotland, the compensa-
summer is at 20 to 30 m., while during the winter it is
ce. In Oslo fjord it was at 10 m. during March. During
n Puget sound it is between 8 and 18 m. Diatoms are
below the compensation depth. They apparently have
nd, though some photosynthesis still takes place at this
t sufficient for long survival. The compensation depth,
mum depth for photosynthesis, is not the same for all
nid-latitudes the optimum depth for a mixed population
s than ten metres, but it is not at the immediate surface.
indicate that the rate of photosynthesis is proportional to
es only at intermediate intensity of illumination. Diatoms
ntense light close to the surface sometimes concentrate
lasts for mutual protection against the light. This is
trophe, and for *Coscinodiscus excentricus,* it takes place
ensity of about 9.69 cal. per square centimetre per hour.
ents (*i.e.,* the dissolved nutrient salts) constitute the in-
supply of the plants. Chief among these are the com-
trogen and phosphorus. The importance of these in the
ytoplankton production was first anticipated in 1899 by
ubsequently, with improved methods of chemical analysis
eatedly been shown to fluctuate with periods of diatom
re is some evidence that iron may be a limiting factor for
al) species according to H. H. Gran. Manganese and
wn accessory growth factors are known to be influential
growth. At best, sea water is only a dilute nutrient
arge concentrations are not needed. For example, a con-
10 mg. of phosphorus to 1,000 l. of water will produce a
vth of diatoms when other factors are favourable.

tion of dilute nutrients is facilitated by the small size of
nkton organism, because with reduction of absolute size
crease in the ratio of surface to volume. Thus, in com-
t 1 mm.^{3} with 1,000 plants of 0.001 mm.^{3} there is a tenfold
rease in surface area of the smaller plants and a hundred-
ment of conditions for diffusion of salts at these surfaces.
s, used in building diatom shells, are drawn upon measur-
iatom growth, but it has not been shown that the reduc-
is sufficient to constitute a limiting factor.

10° C. rise in temperature, within favourable limits, the
olism is increased two- to threefold, according to Jacobus
aw. In the mixed population of the sea the effect is not
ver. The thermal requirements differ for different species,
t that there may be a seasonal succession of different bio-
s, each with its own optimal temperature range. Thus,
ns flourish best during cool periods and are replaced by
waters become warmer. The warmth-loving dinoflagel-
ly dominate during the warmest periods.

a factor significant mainly in maintaining favourable
itions between the organism and the water in which it
pecies are euryhaline (tolerate a wide range of salinity),
enohaline (tolerate only narrow limits). Hence, salinity
lective agency determining the species composition rather
production.

ary factors of phytoplankton production are mainly those
ensity of population. Under favourable conditions of
ts and temperature, the increase in phytoplankton is ex-
l, because the method of reproduction is by simple cell
rough this reproductive habit the population increases by geometrical progression. Cell division may occur as often as twice a day. Nevertheless, the standing crop may at times be small despite favourable primary factors. Any circumstance that operates to withdraw large numbers of individuals must function as a check which affects materially the total numbers that can be produced in a given time. Among the obvious checks are (1) consumption by animals and (2) sinking or transport to unfavourable layers through action of gravity or adverse water currents.

1. Vast quantities of phytoplankton are consumed by the herbivorous zooplankton animals, especially by the copepoda. It has been observed by various investigators that large populations of phytoplankton and zooplankton do not usually exist concurrently in the same area. This disparity is believed to result primarily from heavy grazing by the abundant zooplankton in the area. An alternate hypothesis (animal exclusion) maintains, however, that thick clouds of phytoplankton (diatoms) are avoided by the copepoda, which seek depths below the euphotic zone. A difference in the rate or direction of flow of surface and deep water then tends to segregate the two groups.

2. The rate of sinking of a body heavier than water is controlled by the relation of surplus weight to friction. Most plankton organisms are heavier than water. The small size characteristic of these organisms is, however, an effective adaptation to their floating existence, for with reduction of absolute size there is provided a relatively large friction surface to retard sinking. But, despite this adaptation, there is still a constant loss through the effect of gravity. Many diatoms can be found below the compensation depth, and bottom sediments in certain areas are composed in large part of the shells of diatoms that were produced in surface layers.

A more rapid loss of plants from the zone of optimum light may occur in areas with strong turbulence in passages or channels where surface water and its passive population is shifted to depths of low light intensity. Ascending currents may bring them back to the lighted water, but the period spent by the plants below the compensation depth is a total loss to production. Some degree of stability resulting from increased surface temperature or lowered salinity is therefore advantageous temporarily. However, the advantage gained may result in rapid depletion of the nutrient salts and an accompanying drop in production pending renewal of surface waters by diffusion or by water currents.

Water Currents and Plant Nutrients.—Coincident with the production of a heavy crop of diatoms, there is a sharp drop in the concentration of plant nutrients. Some nutrients are regenerated through bacterial action on dead organisms within the euphotic layer, but there is a continual sinking of organisms and organic detritus from this layer toward the bottom. This effects a serious withdrawal of the nutrient elements from the surface and an accumulation in the deeper water where, because of insufficient light, they cannot be used by plants.

Thus, a deep stratum of water overlying the ocean floor becomes a storehouse for mineralized plant nutrients. It is from this storehouse that (in accordance with A. Nathansohn's theory of 1906) the fertilizing minerals are brought to the lighted surface through the action of ascending water currents. These currents may be of somewhat different origin, but all are of utmost biological importance. In coastal waters, turbulence maintains a more or less steady supply of nutrients in the euphotic zone. In offshore waters there are areas of divergence characterized by a flow of surface waters away from each other and a replacement by deeper water. Such areas are commonly productive. Conversely, the areas of convergence of old surface waters are relatively barren. In boreal regions the convection currents initiated by cooling and sinking of surface waters in autumn and winter replace the surface waters that were depleted because of summer plant growth under conditions of marked water stratification. In these regions there are frequently spectacular spring outbursts of phytoplankton production. Prolonged winds may shift the surface layers and cause temporary currents and upwelling on a small scale. The renewal of nutrients on a grand scale through upwelling of deep water is exemplified by such areas as the west coast of Africa and South America. There the Benguela current and the Peru current, respectively, are laden with nutrients that give rise to notably abundant phytoplankton production that may extend far to sea with the flow of water outward from the coast. In general, coastal areas and shallow banks are more productive than the open sea because it is in these situations that the physical forces are most effective in bringing about renewal of surface water by nutrient-rich subsurface water. (*See* also p. 689.)

Environmental Factors and the Marine Animals.—All animals are of course indirectly dependent upon light for production of primary food. The development of sight has made many forms also directly dependent upon this factor. But the relative independence regarding solar light has made it possible for all depths of the sea to become populated by some type of animal life.

Many of the studies concerning the influence of this factor deal with its control of the vertical distribution of pelagic animals. Characteristically, the copepoda, chaetognatha, some fishes and many other forms have their daytime maximum concentration in depths of 50 m. or more, where the light intensity is much reduced. But with the approach of night many of these animals migrate gradually toward the surface, and return again to deeper water at or before dawn. This behaviour is commonly spoken of as diurnal migration and is a conspicuous phenomenon of the sea. There can be little doubt that light is the motivating stimulus, but its action appears to be in some way linked to geotropism (reaction to gravity). The response to light is not always the same for both sexes, and it sometimes differs also for different stages of development.

In the open ocean there is also a correlation between the amount of light and the colour of pelagic animals. At the surface the colours of fishes are largely silvery or white with backs of green, blue or black. Invertebrates of the plankton are commonly faint red, blue or hyaline. In mid-depths the fishes are silvery and the plankton animals are commonly red or of shades of violet and brown. In abyssal depths the colours tend to uniform shades of red, brown, violet-black or black, without the bizarre markings of shallow-water animals.

Many of the deep-sea forms have structural peculiarities that are associated with absence or reduction of solar light. Conspicuous among these structures are protruding eyes, long tactile organs and light-producing bodies.

Light production (phosphorescence) is not confined to deep-sea animals. Conspicuous among bioluminescent forms are the microscopic Dinoflagellata which live near the surface. At night the crest of waves or the wake of a ship may glow with blue-green light when the water is agitated, causing myriads of these tiny forms individually to emit short flashes.

Together with this glow are usually seen larger, brighter flashes caused by various types of jellyfish and small Crustacea. The light is produced chemically by oxidation of a simple protein called luciferin in the presence of a catalyst called luciferase.

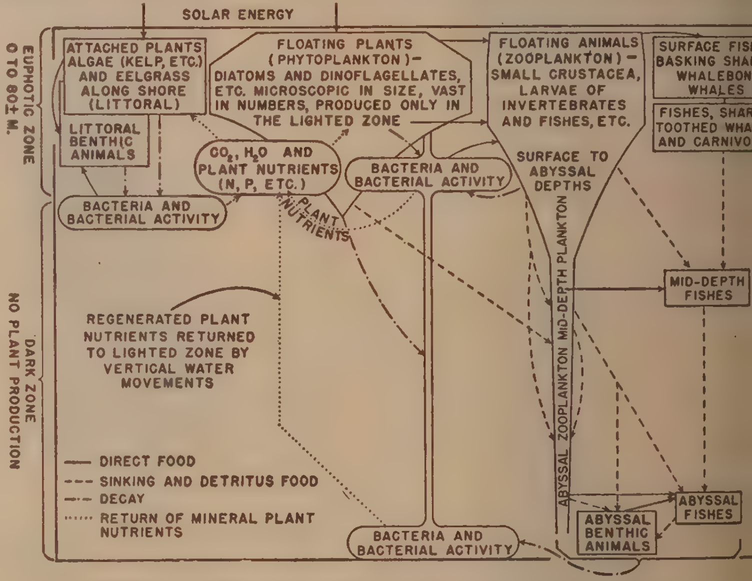
With respect to temperature requirements, animals are either eurythermic, tolerating a wide range of temperature, or stenothermic, tolerating only a narrow range of temperature. Many are eurythermic in the adult stage but are stenothermic with respect to reproduction or to survival in the larval stage. The thermal relationships determine the range of distribution and the spawning season of many species inhabiting the sea. Usually the adults can survive a greater range of temperature than is favourable to successful reproduction, and for this reason they may have an extended area of sterile distribution. These areas are restocked regularly or occasionally by submature or mature migrants from adjacent reproductive areas. Where sharp temperature transitions are lacking along coasts, there also the faunal areas are poorly defined, as is true along the European Atlantic coast and the North American Pacific coast. It frequently happens that animals requiring low temperatures are found in the littoral zone in the higher latitudes, but in the sublittoral or deep-sea zones in the low latitudes. This is known as equatorial submergence.

The salinity of sea water is the one factor which above all other distinguishes the marine environment from other aquatic environments. Most other factors, excepting those associated with the magnitude and depth of the sea, can be duplicated in lakes or streams. Only a few animals like the salmon and eel can migrate, however, from one environment to the other. Many euryhaline coastal forms can endure a marked reduction of salinity for extended periods, but will succumb if sea salts are entirely absent. The stenohaline species (capable of tolerating only a narrow range of salinity) are characteristic of the open ocean, where there are no marked variations in this factor.

In general the animals find an ample supply of oxygen produced by plants or dissolved from the air and distributed by the water currents. Even in the oxygen minimum layer in the open sea some planktonic animals have been found, despite almost complete absence of oxygen. In poorly ventilated basins or bays the decomposition of organic material precipitated from above may lead to exhaustion of the oxygen and development of hydrogen sulphide. In these toxic situations only anaerobic bacteria can exist.

The dependence of animals, directly or indirectly, on the circulation of water in the sea cannot be overstressed. The importance of this factor lies especially in the dispersal of wastes of metabolism, the aeration of the water, the renewal of plant nutrients, the distribution of temperature, the dispersal of temporary and permanent planktonic organisms and the transport of planktonic or detrital food to the many sessile or burrowing benthic animals.

The planktonic organisms, especially the eggs and larvae of the benthic animals (nearly all of which, excepting the deep-sea forms, have pelagic eggs or larvae), live a hazardous existence. T
ways in danger of being transported to areas of unfavour
or to bottoms or depths that are inimical to the adult stag
the period of floating life. To overcome this hazard the s
planktonic young produce a prodigious number of eggs.
systems that form a closed or semiclosed circuit, or where t
are mainly oscillations of the tide such as occur in deep ba
the coasts, the planktonic population is largely endemic; its
history can be studied within the area. Frequently plankto
side areas are swept more or less regularly into these sit
some of the local population may be swept out. If the cha
ditions is not too great, the migrants may live as adults
environment, but they are usually incapable of successful re
The animals that have drifted from their endemic area ar
indicator species and are frequently a material aid in st
source of water masses. Large current systems—for ex
Gulf stream and North Atlantic current—are capable of
a characteristic endemic population of warm-water species.
cooling and by admixture of water from the north, the
species are gradually replaced by the cold tolerant borea
forms.


SOLAR ENERGY
EUPHOTIC ZONE 0 TO 80± M.
DARK ZONE NO PLANT PRODUCTION
ATTACHED PLANTS ALGAE (KELP, ETC.) AND EELGRASS ALONG SHORE (LITTORAL)
FLOATING PLANTS (PHYTOPLANKTON)— DIATOMS AND DINOFLAGELLATES, ETC. MICROSCOPIC IN SIZE, VAST IN NUMBERS, PRODUCED ONLY IN THE LIGHTED ZONE
FLOATING ANIMALS (ZOOPLANKTON) — SMALL CRUSTACEA, LARVAE OF INVERTEBRATES AND FISHES, ETC.
SURFACE FIS
BASKING SHA
WHALEBON
WHALES
FISHES, SHAR
TOOTHED WHA
AND CARNIVO
LITTORAL BENTHIC ANIMALS
CO_2, H_2O AND PLANT NUTRIENTS (N, P, ETC.)
BACTERIA AND BACTERIAL ACTIVITY
SURFACE TO ABYSSAL DEPTHS
BACTERIA AND BACTERIAL ACTIVITY
PLANT NUTRIENTS
ABYSSAL ZOOPLANKTON MID-DEPTH PLANKTON
MID-DEPTH FISHES
REGENERATED PLANT NUTRIENTS RETURNED TO LIGHTED ZONE BY VERTICAL WATER MOVEMENTS
— DIRECT FOOD
--- SINKING AND DETRITUS FOOD
-·- DECAY
······ RETURN OF MINERAL PLANT NUTRIENTS
BACTERIA AND BACTERIAL ACTIVITY
ABYSSAL BENTHIC ANIMALS
ABYSSAL FISHES

FROM H. U. SVERDRUP, M. W. JOHNSON AND R. H. FLEMING, "THE OCEANS" (PRENTICE-HALL, INC., 1942)

THE MAIN FEATURES OF THE INTERRELATIONS OF MARINE ORGANISMS

The Role of Bacteria in the Sea.—The role of bact
metabolism of the sea is concerned mainly with transfor
organic material to the inorganic or mineral state and no
production or storage of organic material. There are a few a
marine bacteria (capable of synthesizing organic material
organic material produced by them is negligible. Most bact
sea are heterotrophic; *i.e.*, they obtain their energy for lif
through the oxidation of organic compounds. These comp
be in the particulate state as plant or animal tissue, or they
solution in the water. There is evidence that the organic
solution in the sea is several times greater than that occu
standing crop in the particulate state. The concentration
solved matter is remarkably uniform, and it is believe
upper limit of concentration represents a threshold value ma
a level below ten milligrams per litre by the bacteria. Since
only the mineralized nutrients, this reclaiming of dissolved
conversion to simple mineralized plant nutrients by bact
sential to the biological cycle of the sea. Equally importa
transformations through bacterial decomposition of the
organic matter.

In the process of bacterial decomposition of organic
series of steps is involved, each with its specific types
Thus, a step in the nitrogen cycle is the simplification of
molecule by splitting off the NH_2 group from the amino ac
types of bacteria can do this. At this point the nitrogen may
lated by the diatoms. However, the cycle is usually carri
by the nitrifying bacteria forming nitrates from ammonia
($NH_3 \rightarrow NO_2 \rightarrow NO_3$). Ammonia may also be oxidized to nit
chemically. The cycle is somewhat further involved by t
of nitrate-reducing and -denitrifying bacteria, which may
chemical process at least in part ($NO_3 \rightarrow NO_2 \rightarrow N_2$). This
to occur in environments lacking or poor in oxygen, where t

oxygen by reducing these compounds. True denitrifiers
ogen fixers appear, however, to be unimportant in the
he sea.

, carbon and sulphur cycles are also activated by bacteria.
s, the phosphates are quickly regenerated, but renewal of
n nature appears to require three to four months. The
anic compounds is returned as carbon dioxide, which is
t in ample quantity for plant growth. A small amount
used by plants in the form of sulphates, but an important
ganic decomposition is hydrogen sulphide which, when
e quantities, is inimical to plant and animal life.

tion of bacteria in the sea is governed by the distribution
organic material. Hence, two centres of large bacterial
cur. One of these is within the euphotic zone, where the
and zooplankton are abundant. The second is on the
organic material accumulates as a result of sinking of
nekton from the overlying water. Most bacteria are
, grow attached to solid surfaces such as diatoms, copep-
grains. Therefore, relatively few appear to be truly

ding features of the interrelations of marine organisms
ganic-inorganic cycle are diagrammatically shown in the

ent of Organic Production in the Sea.—Gross
ction is defined as the amount of organic material syn-
inorganic material by autotrophic organisms in unit
olume of water or unit area of sea surface.

of production commonly used are briefly as follows:

sus.—By this method the individual plants (diatoms or
) from a known quantity of water are counted under a
d the results are reported as cells per litre or cubic metre
situ. Counts from isolated observations are, of course,
nents of the standing crop. To obtain an estimate of
an interval of time, successive samples are needed, to-
ta on the rate of reproduction and consumption in the
riods.

, though essential to the analysis of the biological groups,
by itself to show the volume of production, hence com-
thods, mainly chemical, are used.

ment analysis.—This consists of extracting (with ace-
nents from the plants of a known volume of water and
ing the pigment units, each unit being equivalent to
of organic carbon.

roduction. For each 0.536 mg. of carbon assimilated by
ton there is set free 1 ml. of oxygen. One experiment
Maine showed a maximum production of 2.33 ml. per
at the surface in about nine hours, while the whole
1 m.^{2} × 44 m. deep produced 29.1 l. of oxygen; *i.e.*, a
gr. of carbon.

rient consumption. A rather constant ratio exists be-
nitrogen and phosphorus in the organic content of
n. The ratios C:N:P=41:7.2:1 by weight are about
is for these elements in sea water. The drop in con-
the mineralized state of any of these elements in sea
period of time is therefore a good index of the extent
organic substance that has taken place (plus an un-
y equal to the nutrients that have been regenerated dur-

tes of organic production are based upon the quantity
lants, of course, are the only real producers in the sea,
y of animals produced in a given area must depend upon
the area to produce plants. Therefore, the productivity
y be judged roughly by the amount of zooplankton it
some instances, by the products of fisheries.

is usually reported as numbers of cubic centimetres per
water or per square metre of ocean surface. In the
, where the copepod *Calanus finmarchicus* dominates
the concentration of this animal was found to be from
er cubic metre over a large part of the gulf. The stand-
copepod plankton for the whole gulf was of the order
ns. The crop increase between May and September was
,000,000 tons.

ion of fisheries products with plankton production is
nt in connection with the plankton-feeding fishes such
herring, etc., and with the catches of whalebone whales.
f California, for example, the upwelling of water at the
to a rich crop of phytoplankton and zooplankton, and
about 550,000 tons of sardines alone have been fished
s is equivalent to more than a ton a minute throughout

g operations are carried on in the waters of the Ant-
ding grounds of the blue whale and other species that
animal plankton.

f these areas are also notably rich in plant nutrients and
zooplankton.

ce of benthic animals in many coastal areas, and in rich
Puget sound, is also a reflection of the heavy plant pro-
takes place there. In contrast, there is a scarcity of
great ocean depths. This scarcity results partly from the small production of plankton in the surface waters of the open sea (as explained earlier) and partly from the dissolution of the surface products before they reach the bottom in their course of sinking.

(*See* also WAVES OF THE SEA; ZOOLOGICAL COLLECTING: *Marine Collecting.*)

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OME DIGENETIC TREMATODES, INCLUDING EIGHT NEW SPECIES, FROM MARINE FISHES OF LA JOLLA, CALIF.[1]

By Harold W. Manter and Harley J. Van Cleave

N April and May, 1940, one of us (Van Cleave) carried on a eliminary investigation of the worm parasites of marine fishes southern California. The Scripps Institution of Oceanography, ough its director, Dr. H. U. Sverdrup, very generously proled facilities, and Dr. Denis Fox extended privileges of his oratory, while Percy Barnhart aided in the collection and ntification of the fishes. In the vicinity of La Jolla approxitely 200 individual fishes were examined, representing 34 ecies. Two papers have been published previously on the Acancephala encountered (Van Cleave, 1940, 1945), and another in preparation. The present report is based wholly upon the enetic trematodes recovered from 16 species of fishes, but in ne instances the trematodes were either immature or so few as render identification impossible. Several of the hosts from ich no trematodes were taken were represented by one or a y few autopsies; consequently for these hosts the negative recls are without significance. More extensive sampling would be eded before a faunal list approaching completeness could be esented.

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tudies from the Department of Zoology, University of Nebraska, No. 249; Studies from the rtment of Zoology, University of Illinois; and Contributions from the Scripps Institute of nography, new series, No. 482.

The writers are especially indebted to Mrs. Jean A. Ross f staining and mounting the specimens, to Mrs. Katharine Hill Pa for most of the drawings that illustrate this report, and to I Carl L. Hubbs for checking the names of the fish hosts.

All hosts are from the vicinity of La Jolla in southern Ca fornia unless other localities are cited. All the croakers and co binas (family Sciaenidae) were taken by line fishing from t Scripps Laboratory pier at La Jolla. Most of the other fishes we collected by seining in shallow waters and tide pools or were c tained from commercial fishermen.

In this study 17 species of digenetic trematodes are recogniz from marine fishes, of which 8 are regarded as previously u described. In the collections available for study there are unsat factory representatives of two additional species, but the mater is not adequate to serve as the basis for describing these as ne species. One is a species of the genus *Phyllodistomum* (fami Gorgoderidae) from *Fundulus parvipinnis parvipinnis* Girard, a the other is an undescribed species of the genus *Lepidapedon* (fa ily Lepocreadiidae) from *Mycteroperca pardalis* Gilbert, fro Mazatlán, Gulf of California. The former is represented by single individual and the latter by two broken specimens, both which lack the anterior extremity including the oral sucker. V prefer to withhold descriptions of these in the hope that so other worker may discover more adequate material on which base the species.

For each new species described in this report a holotype h been designated and is deposited in the United States Natio Museum as a stained whole mount in clarite. All additional spe mens of the new species are regarded as paratypes, and as far available these are deposited in our own collections at Linco Nebr., and Urbana, Ill., respectively, and in the United Stat National Museum.

A total of nine families of digenetic trematodes are represent in the collection under consideration, of which the family Op coelidae had the widest representation of genera and species well as of individual specimens. In the text descriptions are a ranged by families of the trematodes. A list of fish hosts, with t trematodes encountered in each, is given on pages 336–337.

Previously there have been few studies of trematodes of fish from the Pacific coast of this continent. Chief of these are t publications of Lloyd, McFarlane, Noble, Annereaux, and Pa while Manter (1940) has described a few species from the Mexic coast. The trematode fauna of southern California has been b little known. Sleggs (1927) reported *Otodistomum cestoid*

= *Distomum veliporum* of Sleggs) from *Raja bituberculata*[2] at La lla, and a hemiurid, which he called *Distomum appendiculatum*, om *Paralichthys californicus*, presumably also from La Jolla. is latter species is too incompletely described to permit of its entification. In the present study an immature hemiurid from e same host could not be identified as to genus.

Order GASTEROSTOMATA

Family BUCEPHALIDAE

Genus BUCEPHALOPSIS Baer, 1855

BUCEPHALOPSIS LABIATUS, new species

PLATE 12, FIGURES 1, 2

Description (measurements based on nine specimens).—Small, oid gasterostomes, 0.635 to 0.745 mm. long by 0.234 to 0.328 m. wide, widest near anterior end. Anterior sucker (as) 0.127 0.146 mm. in transverse diameter. Mouth posterior to midbody, sually about two-thirds body length from anterior end, with a con-icuous anterior oral lobe or lip (ol). Pharynx (ph) ovoid, wider an long, 0.071 to 0.080 mm. in transverse diameter; esophagus tending anteriorly, gradually widening to become the cecum c), which curves backward from near posterior edge of ovary that the digestive system is inverted **U**-shaped, ending slightly nterior to level of the mouth. Testes (t) ovoid, diagonal; anterior stis approximately at midbody level and mostly anterior to outh. Cirrus sac (cs) long and slender, almost uniform in width, xtending anterior to mouth to midbody or beyond; 0.314 to 0.360 m. long by 0.066 to 0.073 mm. wide; seminal vesicle an ovoid ac 0.076 to 0.078 mm. long by 0.046 to 0.070 mm. wide; atrial ube moderately long, 0.060 to 0.087 mm.; genital pore ventral, ear posterior end of body. Ovary (ov) globular, immediately nterior to anterior testis; vitelline follicles (v) fused to form wo irregular longitudinal masses at ovarian level, meeting near nterior end of ovary, diverging slightly posteriorly, usually seem-ng to be displaced toward one side of the body; vitelline duct rom each mass extends posteriorly to meet near intertestis level nd some distance posterior to ovary; uterus (ut) extends an-eriorly near right edge of body from near union of yolk ducts, eaching to anterior sucker, extending posteriorly to right of vary, a short metraterm leads to the genital atrium (ga). Un-ollapsed and normal eggs 25 to 31μ by 16 to 17μ. Excretory pore erminal; excretory vesicle (ex) extending to near base of anterior ucker.

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[2] Probably a lapsus calami for *Raja binoculata*.

Host.—*Paralichthys californicus* (Ayres), California halibu
Location.—Intestine.

Types.—Holotypes and paratypes, U.S.N.M. Helm. Coll. 37142.

Discussion.—The name *labiatus* is from *labium,* lip, and refer the preoral lip (ol, pl. 12, figs. 1, 2), which is not present in other species in the genus. Uncommon features are the poster location of the mouth, the reduced and contiguous vitellaria, long excretory vesicle, the curved cecum, and the long cirrus The species most similar to *B. labiatus* seems to be *B. kar* Bhalerao, 1937, from *Belone* in the Indian Ocean. The two spe agree in small body size, mouth posterior to midbody, and ci sac reaching anterior to midbody; but differ in that *B. karvei* vitellaria in two widely separated groups, does not have a recur cecum, lacks the preoral lip, and has smaller eggs. *B. magnace bulum* Nagaty, 1937, from *Belone choram,* in the Red Sea, sembles and differs from *B. labiatus* in the same respects exc that its cirrus sac is relatively shorter. It may be found t *B. karvei* and *B. magnacetabulum* are a single species.

The occurrence in Belonidae of species of trematodes apparen most similar to a species occurring in sinistral flat fishes (Bo dae) suggests the host distribution of the species of *Steganode* (Manter, 1947, p. 312). Neither the ecology nor the phylog of these families of fishes indicates any relationship that wo be suggested by their trematode parasites.

Order PROSOSTOMATA

Family OPECOELIDAE

Genus OPECOELUS Ozaki, 1925

OPECOELUS ADSPHAERICUS, new species

Plate 12, Figures 3–5

Description (based on about 60 specimens with measureme on 7 individuals selected for size range).—Body elongate, cy drical, smooth, 1.336 to 4.004 mm. long by 0.167 to 0.409 mm greatest width. Oral sucker 0.084 to 0.146 in diameter; acetabu 0.112 to 0.255 mm. in diameter. Sucker ratio 1:1.33 to 1.66. Ace ulum protuberant; with three pairs of short, rather in spicuous, lobelike, simple papillae (ap, pl. 12, fig. 4), barely cernible when retracted. Often only lateral views of the suck are presented; measurements of depths rather than transv diameters give similar sucker ratio. Forebody 0.197 to 0. mm. or about one-fifth to one-eighth body length. Posttestic stance 0.380 to 1.219 mm. or about one-third to one-fourth body ngth and about twice length of forebody. Prepharynx short; arynx 0.051 to 0.095 mm. long by 0.051 to 0.102 mm. wide; ophagus 0.119 to 0.153 mm. long or about 1½ times length of arynx; intestinal bifurcation near anterior edge of acetabulum; ca uniting and opening through a ventral anus (a, fig. 3) slightly terior to posterior end of body.

Genital pore slightly to the left, opposite anterior half of esopha- us, varying from near base of pharynx to about midesophageal vel. Testes rounded to elongate, smooth, tandem, almost always parated by vitellaria (only one apparent exception); anterior stis about at midbody level. Cirrus sac (cs, fig. 5) elongate riform, 0.102 to 0.110 mm. long in medium-sized specimens, ostly anterior to intestinal bifurcation, containing a short cirrus ir), a tubular prostatic vesicle, and a few inconspicuous gland lls (fig. 5) surrounding male tube immediately outside cirrus c; seminal vesicle (sv) external, tubular, sinuous, extending a ort distance posterior to acetabulum. Ovary indistinctly 3-lobed; minal receptacle lacking; uterus preovarian; eggs 49 to 59 by 5 to 38μ; uncollapsed eggs near ovary 49 to 59μ by 32 to 38μ; llapsed eggs 51 to 56μ by 25 to 32μ. Anterior extent of vitelline llicles varying from base of cirrus sac to posterior edge of acetab- um; follicles almost always interrupted opposite one or both stes and usually opposite ovary, almost always confluent between stes and usually between ovary and anterior testis, filling post- sticular space. The vitelline follicles are unusually variable in is species. Excretory pore terminal; excretory vesicle extending near ovary.

Hosts.—*Clinocottus analis australis* Hubbs, tide-pool woolly ulpin; *Girella nigricans* (Ayres), the common opaleye.

Location.—Intestine.

Types.—Holotype and paratye, U.S.N.M. Helm. Coll. No. 37143.

Discussion.—The following 12 species of *Opecoelus* have been amed: *elongatus* Ozaki, 1925; *gonistii* Yamaguti, 1938; *inimici* amaguti, 1934; *lobatus* Ozaki, 1925; *mexicanus* Manter, 1940; *inor* Yamaguti, 1934; *mutu* Yamaguti, 1940; *ozakii* (Layman, 930) Yamaguti, 1938; *quadratus* Ozaki, 1928; *sebastodis* Yama- uti, 1934; *sphaericus* Ozaki, 1925 (type species); *xenistii* Manter, 940.

Of these species, three (*sphaericus*, *minor*, and *sebastodis*) are tremely similar. Yamaguti himself (1934) confused *O. minor* nd *O. sebastodis*, finally deciding (1940) that the latter differed rom the former only in shorter acetabular papillae and larger

eggs (54 to 65μ by 30 to 38μ for *minor* as compared with 63 to
by 40 to 45μ for *sebastodis*). He expressed the view that
measurements differed considerably between living and preser
specimens, yet most descriptions do not indicate whether meas
ments are made on living or fixed material. Also, it seems unu
that Yamaguti should claim considerably larger egg sizes for
served material as compared with living. Actually, his living
sizes for *O. minor* agree well with measurements on two
served specimens of *O. minor* sent to one of us (Manter) by Ya
guti several years ago. Thus, *O. minor* can be distinguished f
O. sphaericus by its longer acetabular papillae and smaller e
(72 to 81μ by 41 to 47μ for *sphaericus*). The rather small sp
mens from a "black eel" reported as "probably" *O. sphaericus*
Yamaguti (1940 p. 73) would seem to be doubtfully that spec
Their sucker ratio and egg sizes are much more like *O. minor*

The corrections by Yamaguti mentioned above make *O. se*
todis more like *O. sphaericus*. Egg sizes agree as well as body
portions. The only difference discernible from descriptions is
of body size (1.6 to 3.4 mm. length for *sebastodis*, 4.3 to 8.25
for *sphaericus*). Until and unless further constant differences
be found, *O. sebastodis* should be considered a synonym of
sphaericus.

Opecoelus adsphaericus differs from *O. minor* only in hav
short, inconspicuous acetabular papillae and a more ante
genital pore. Even when the acetabulum is greatly extended
papillae are usually very short in *O. adsphaericus*. In only 3 sp
mens of more than 60 did the papillae seem to be at maximum
tension measuring up to 0.036 mm. in length. In two specimen
O. minor available for study, each of which was almost exa
the size of the above specimens of *O. adsphaericus*, the pap
measured 0.050 and 0.072 mm., while Yamaguti states they r
0.118 mm. His figure shows them about as long as the dept
the acetabulum itself, a condition never approached in *O.*
sphaericus. Also, in *O. minor* the papillae have a thick o
layer of cuticula. The two species agree in shape and locatio
reproductive organs and in egg size. Sucker ratios are diff
to compare, as Yamaguti's original figures indicate a ratio of 1
for *O. minor* but his fig. 46 (1934), which he later (1940) clai
to be *O. minor* rather than *O. sebastodis* as labeled, shows a rati
more than 1:2. We do not feel it possible to identify our specin
as *O. sphaericus* (= *O. sebastodis*) because of two differen
O. adsphaericus has a genital pore opposite the anterior hal
the esophagus and an egg size of 49 to 59μ by 26 to 24μ (as c
pared with 72 to 81μ by 44 to 47μ). Our specimens are consi

bly smaller than the sizes originally given for *O. sphaericus* but ot smaller than *O. sebastodis*. Unfortunately, in *O. adsphaericus* he extent of the vitelline follicles is unreliable as a diagnostic aid, ince both their anterior extent and their interruption opposite he testes varied in our material. However, in *O. adsphaericus* the ollicles are almost always interrupted opposite the testes, whereas)zaki states (1928, p. 12) that in *O. sphaericus* they are usually ontinuous but may be discontinuous opposite the gonads.

A series of 11 specimens of *Opecoelus* from the intestine of *irella nigricans* (Ayres) showed some fairly consistent differnces from those taken from *Clinocottus*. In individuals from *irella* the pharynx was often somewhat larger, with reference to iameter of the oral sucker, than was typical for individuals rom *Clinocottus;* likewise the eggs averaged larger, and the oral apillae were in some instances longer and more pointed. Howver, in some individuals from *Girella*, measurements of these deails fell distinctly within the range established for the series from *linocottus*. Consequently it seems admissible to identify the pecimens from *Girella* as *Opecoelus adsphaericus* and in so doing o recognize considerable individual variability within this species.

The name *adsphaericus* indicates the similarity of the species to *). sphaericus*.

Related genera occur in the Atlantic, but as yet the genus *)pecoelus* is reported only from Japanese waters and from the merican Pacific coast.

Genus PSEUDOPECOELUS von Wicklen, 1946

PSEUDOPECOELUS GIBBONSIAE, new species

PLATE 12, FIGURES 6, 7

Description (based on two specimens).—Body (pl. 12, fig. 6) ather thick, unspined, 2.262 to 2.558 mm. in length, 0.643 to 0.780 nm. in thickness at acetabular level. Oral sucker (os) 0.179 to .195 mm. in length; 0.187 to 0.195 mm. in thickness. Acetabulum ac) slightly protuberant, without papillae; 0.421 to 0.468 mm. in ength; 0.382 to 0.429 mm. in depth. Ratio of sucker lengths, 1:2.35 o 2.4. Acetabulum 0.773 to 0.811 mm. or about one-third body ength from anterior end. Prepharynx 0.055 to 0.086 mm. in length. Pharynx (ph) large, 0.163 to 0.179 mm. long by 0.179 to 0.195 mm. hick. Esophagus frequently longer than pharynx, 0.269 mm. long n the 2.558 mm. specimen, in which the pharynx was 0.179 mm. ong. Ceca (ic) ending blindly near posterior end of body. Genital ore (gp) ventral, slightly to the left, opposite posterior fourth f pharynx; accessory suckers lacking. Testes (t) smooth, subpherical, tandem, contiguous, in midregion of hindbody; post-

testicular space 0.523 to 0.577 mm. Seminal vesicle (sv) a rel
tively narrow sinuous tube extending from near the genital po
posterior to acetabulum almost to ovary; cirrus very short; cirr
sac lacking; a few gland cells (pl. 12, fig. 7) in region of genit
pore. Ovary globular, smooth, immediately pretesticular, slight
to the right; seminal receptacle lacking; sperm cells in uteru
Mehlis' gland very large and conspicuous; vitelline follicles (
large, extending from a point about midway between pharynx a
acetabulum continuously to posterior end of body, surrounding t
ceca. Uterus preovarian; metraterm lacking; eggs 90 to 92μ
36 to 47μ, when uncollapsed 90 to 92μ by 43 to 47μ. Excreto
vesicle extending to posterior edge of ovary.

Host.—*Gibbonsia metzi* Hubbs, weed sawfish.

Location.—Intestine.

Holotype.—U.S.N.M. Helm. Coll. No. 37145.

Discussion.—The genus *Pseudopecoelus* contains the followi
species: *vulgaris* (Manter, 1934) Von Wicklen, 1946; *japonic*
(Yamaguti, 1938) Von Wicklen, 1946; *elongatus* (Yamagu
1938) Von Wicklen, 1946; *tortugae* Von Wicklen, 1946; *priacant*
(MacCallum, 1916) Manter, 1947. *P. gibbonsiae* differs from
these in that its vitellaria extend anterior to the acetabulu
P. vulgaris and *P. japonicus* have a lobed ovary. *P. elongatus* h
a more posterior genital pore and smaller eggs, and its vitella
are interrupted opposite the gonads. *P. tortugae* has a more po
terior genital pore, much longer hindbody and uterus, and small
eggs. *P. priacanthi* has a different sucker ratio and much small
eggs.

PSEUDOPECOELUS UMBRINAE, new species

PLATE 12, FIGURES 8, 9

Description.—This species has the generic characters of *Ps*
dopecoelus, namely: smooth body; acetabulum without papilla
no accessory sucker; ceca ending blindly; no cirrus sac; sho
cirrus; and tubular seminal vesicle. Length 1.037 to 2.420 mn
greatest width (near posterior end or at acetabular region) 0.4
to 0.873 mm. Body tapering from acetabular level to anterior e
broadly rounded posteriorly. Forebody 0.292 to 0.584 mm.
length or approximately one-fourth body length; a little grea
or a little less than posttesticular space. Oral sucker 0.124 to 0.1
mm. in transverse diameter; acetabulum 0.219 to 0.365 mm.
transverse diameter, slightly wider than long, with transve
aperture. Sucker ratio 1:1.65 to 2. Acetabulum usually sligh

ss than twice the diameter of oral sucker. Prepharynx short; iarynx 0.061 to 0.095 mm. in length by 0.075 to 0.124 mm. in idth; length of esophagus one to two times length of pharynx; testinal bifurcation a short distance anterior to acetabulum; ca ending blindly a short distance anterior to posterior end of ody.

Genital pore (gp, pl. 12, figs. 8, 9) muscular, slightly to left of idline at midpharyngeal level. Testes (t, pl. 12, fig. 8) large, ndem or slightly diagonal, close together, smooth or slightly regular in outline. Posterior testis usually with a slightly innted outline. Cirrus (cir, fig. 9) very short; prostatic vesicle ov) small and ovoid; seminal vesicle (sv) sinuous, somewhat ore swollen posteriorly, extending dorsal to acetabulum to midetabular level or to near posterior edge of acetabulum; cirrus c lacking. Ovary 3- or 4-lobed (ov, fig. 8), partly to the right id partly anterior to anterior testis. Uterus beginning to left of vary, mostly preovarian. Seminal receptacle and metraterm lackg. Vitelline follicles (v, fig. 8) large, extending from posterior id of esophagus to posterior end of body; lateral, dorsal, and entral to ceca; anterior to acetabulum they are lateral and dorsal it only scantily dorsal to ceca; confluent posterior to testes; alost confluent anterior to acetabulum. Eggs 61 to 71μ (rarely to 0μ) by 27 to 49μ; collapsed eggs 61 to 68μ by 27 to 32μ; unllapsed eggs near ovary and probably more nearly representing ie size of living eggs, 68 to 71μ by 42 to 49μ. Excretory vesicle ctending forward almost to ovary.

Host.—*Umbrina roncador* Jordan and Gilbert, yellowfin croaker.

Location.—Intestine.

Types.—Holotype and paratype, U.S.N.M. Helm. Coll. No. 37146.

Discussion.—*P. umbrinae* differs from all species in the genus, xcept *P. gibbonsiae,* in that the vitellaria extend anterior to the cetabulum. It is the only species in which the seminal vesicle does ot extend posterior to the acetabulum. The acetabulum is relavely larger than in *P. japonicus, P. elongatus,* or *P. tortugae,* nd relatively smaller than in *P. vulgaris.* It differs from *P. gibonsiae* in its lobed ovary, smaller pharynx, more flattened body, nd much smaller eggs.

Genus HELICOMETRINA Linton, 1910

HELICOMETRINA ELONGATA Noble and Park, 1937

PLATE 13, FIGURE 10

Hosts.—*Clinocottus analis australis* Hubbs,[3] tide-pool woolly culpin; *Gibbonsia elegans* (Cooper),[3] ocellated sawfish; *Gibbonsia ietzi* Hubbs,[3] weed sawfish.

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[3] New host record.

Location.—Intestine.

Discussion.—The previously recorded host for this species *Sicyogaster maeandrica* (= *Caularchus maeandricus*), Bode Bay, Calif.

This species is distinguished from *H. nimia* in that the vitelli follicles (v, pl. 13, fig. 10) are interrupted near the acetabulu the genital pore is anterior to the intestinal bifurcation, and t ovary (ov) has four rather than three lobes. These distinctio held for all of about 37 specimens from *Gibbonsia* and almost of 20 specimens from *Clinocottus,* although rarely the vitellar were continuous on one side. Three specimens from *Clinocott* confuse the picture somewhat. These have continuous vitellaria, genital pore posterior to the bifurcation, and an ovary eith with four lobes or with lobes too indistinct to count. Perhaps the specimens are *H. nimia,* which is already known to have a wi host and geographical distribution and has been reported fro the Pacific (Galápagos Islands). However, numerous specime of *H. nimia* from both Tortugas, Fla., and the Galápagos Islan agree in that the three or four primary lobes of the ovary a secondarily lobed and the testes are not rounded as in *H. elonga* but wider than long and irregular in outline, sometimes almo lobed. For the present it seems best to consider the round test and the 4-lobed ovary as characters distinguishing *H. elonga* from *H. nimia.* However, a conspicuous interruption of the vit line follicles and a more anterior genital pore seem to be at lea almost always characteristic of *H. elongata* and perhaps nev occur in *H. nimia.*

Genus GENITOCOTYLE Park, 1937

GENITOCOTYLE ACIRRATA Park, 1937

Hosts.—*Damalichthys vacca* Girard,[3] pileperch; *Umbrina ro cador* Jordan and Gilbert,[3] yellowfin croaker.

Location.—Intestine.

Number.—One in a single specimen of each host species.

Discussion.—A specimen of *G. acirrata* sent to one of us (Ma ter) several years ago was available for comparison. It is believ that Park's so-called "pars prostatica" is actually a thick-wall cirrus with circular muscles especially conspicuous. Thus, the nar given to the species is probably inappropriate.

This species is known previously only from *Holconotus rhod terus* Agassiz, the porgy or surfperch, from Dillons Beach, Cal

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[3] New host record.

Genus PLAGIOPORUS Stafford, 1904

PLAGIOPORUS ISAITSCHIKOWI (Layman, 1930) Yamaguti, 1938

Host.—Paralabrax clathratus (Girard),[3] kelp bass.

Location.—Intestine.

Discussion.—Three specimens, in only fair condition and showg only a lateral view, are identified as this species. They agree ith Yamaguti's description in such characteristic details as vitlaria interrupted opposite acetabulum; testes tandem; genital re opposite pharynx; uterus extending to posterior edge of anrior testis; ceca ending a little beyond posterior testis. However, e cirrus sac extends to a little past midacetabular level (rather an ending close to anterior border) and the largest eggs in tero were 48 by 34μ as compared with 57 to 63μ by 38 to 40μ scribed for *P. isaitschikowi.* Contraction of the forebody might fect somewhat the posterior extent of the cirrus sac. The difrence in egg size is considerable, but Yamaguti does not state hether his measurements were from preserved specimens. The cker ratio on our specimens could not be determined because f the lateral view. *P. isaitschikowi* has been previously reported om *Sebastiscus albofasciatus,* from Suruga Bay, Japan, and from eter the Great Bay.

Genus OPECHONA Looss, 1907

OPECHONA ORIENTALIS (Layman, 1930) Ward and Fillingham, 1934

PLATE 13, FIGURES 11, 12

Host.—Girella nigricans (Ayres),[3] common opaleye.

Location.—Intestine.

Number.—Several specimens, some immature.

Discussion.—These trematodes agree well with those reported rom *Paranthias furcifer,* a "small mackerel," and *Angelichthys* p., from the Mexican coast and the Galápagos Islands (Manter, 940). A young specimen shows that the "branch of the excretory esicle" on the left side of the body actually is represented on both ides (pl. 13, figs. 11, 12). When swollen, these lateral trunks or ubes (lt) are fairly conspicuous, extending from near the inestinal bifurcation to a short distance posterior to the testes where ach seems to have an inconspicuous union with the excretory esicle (ex, fig. 12). The median trunk of the excretory vesicle mt) extends forward ventral to the intestinal bifurcation to end ust posterior to the pharynx. It often contains round, deeply taining concretions. However, this median tube is separated by a arrow constriction from that portion of the vesicle posterior to the testes (fig. 12), and thus may be homologous to the later excretory tubes. The lateral tubes do not occur in *Opechon pharyngodactyla.*

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[3] New host record.

Family ACANTHOCOLPIDAE

Genus STEPHANOSTOMUM Looss, 1899

Stephanostomum Looss, 1899, p. 576.
Stephanochasmus Looss, 1900, p. 603.
Lechradena Linton, 1910, p. 46.
Echinostephanus Yamaguti, 1934, p. 374.

More than 30 species of *Stephanostomum* have been named. (these, three—*Stephanochasmus hystrix* (Dupardin, 1845, Olsson) Looss, 1899; *S. robustus* MacCallum, 1917; and *Stephano tomum sobrinum* (Levinsen, 1881) Looss, 1899—are insufficient described. Since the genus is a large one and widely distribut among marine fishes, a list of species and a key to aid in the identification is presented.

For many years species in this genus were considered in tl genus *Stephanochasmus,* which Looss (1900) named for the because he considered *Stephanostomum* invalidated by *Stephano toma* Danielsen and Koren, 1880. As *Stephanochasmus* speci were transferred to *Stephanostomum,* the literature frequently d not clearly indicate the authors of new combinations. Of tl species in the following list, Dawes (1946) seems to have fir used the combination in one case, while four seem to be new cor binations. Synonyms of only the new combinations are list here.

SPECIES OF STEPHANOSTOMUM

anisotremi Manter, 1940
baccatum (Nicoll, 1907) Manter, 1934
bicoronatum (Stossich, 1883) Manter, 1940
caducum (Looss, 1901) Manter, 1934
californicum (p. 328), new species
casum (Linton, 1910) McFarlane, 1936
cesticillum (Molin, 1858) Looss, 1899 (type species)
cloacum (Srivastava, 1938), new combination; synonym *Echinostephan*
  cloacum Srivastava, 1938
coryphaenae Manter, 1947
dentatum (Linton, 1900) Manter, 1931
ditrematis (Yamaguti, 1939) Manter, 1947
elongatum (Park, 1939) Hanson, 1950
fistulariae (Yamaguti, 1940) new combination; (synonym *Echinoste*
  anus fistulariae Yamaguti, 1940)
hispidum (Yamaguti, 1934) Manter, 1940
imparispine (Linton, 1905) Manter, 1940

japonicum (Yamaguti, 1934), new combination; (synonym *Stephanochasmus japonicus* Yamaguti, 1934)
lineatum Manter, 1934
megacephalum Manter, 1940
microstephanum Manter, 1934
minutum (Looss, 1901) Manter, 1940
multispinosum Manter, 1940
pristis (Deslongchamps, 1824) Looss, 1899
promicropsi Manter, 1947
rhombispinosum (Lebour, 1908) Manter, 1934
sentum (Linton, 1910) Manter, 1947
tenue (Linton, 1898) Linton, 1940
triglae (Lebour, 1908) Dawes, 1946
tristephanum McFarlane, 1935

KEY TO SPECIES OF STEPHANOSTOMUM

1 (6) Three rows of oral spines 2
2 (5) Spines very numerous (140 or more) 3
3 (4) Vitellaria extending anterior to acetabulum .... **microstephanum**
4 (3) Vitellaria not reaching acetabulum .... **tristephanum**
5 (2) Spines 50 to 52 .... **lineatum**
6 (1) Two rows of oral spines 7
7 (14) Vitellaria interrupted opposite testes 8
8 (9) Oral spines rhomboid .... **rhombispinosum**
9 (8) Oral spines elongate 10
0 (11) Oral spines 36; vitellaria not reaching cirrus sac .... **pristis**
1 (10) Oral spines at least 48; vitellaria reaching cirrus sac 12
2 (13) Sucker ratio 1:1 .... **caducum**[4]
3 (12) Sucker ratio 1:2 .... **promicropsi**
4 (7) Vitellaria not interrupted opposite testes 15
5 (28) Vitellaria extending to posterior edge of acetabulum 16
6 (17) Oral sucker larger than acetabulum .... **fistulariae**
7 (16) Oral sucker smaller than acetabulum 18
8 (19) Oral spines very numerous (about 80) .... **multispinosum**
9 (26) Oral spines considerably fewer than 80 20
0 (23) Eggs 96 to 126μ long 21
1 (22) Suckers subequal .... **triglae**
2 (21) Sucker ratio about 1:1.4 to 1.6 .... **japonicum**
3 (20) Eggs 56 to 80μ long 24
4 (25) Oral spines 24 .... **elongatum**
5 (24) Oral spines 36 or more 26
6 (27) Oral spines 36; prepharynx considerably longer than pharynx .... **casum**
7 (26) Oral spines 48 to 50; prepharynx not considerably longer than pharynx .... **dentatum**
8 (15) Vitellaria not reaching acetabulum 29
9 (40) Vitellaria reaching only to base of cirrus sac or slightly beyond 30
0 (31) Oral spines 56; eggs 87 to 101μ .... **baccatum**[5]

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[4] Lebour's (1907) specimen of *S. caducum* from the whiting did not have interrupted vitellaria. t may represent another species. It is much like *S. ditrematis* except for its equal suckers.

[5] Nicoll's original specimen of *S. baccatum* had vitellaria extending only to base of cirrus sac. le later described a somewhat more anterior extent but not to the acetabulum. Manter's (1926) gure shows the vitellaria to the acetabulum. Thus, there is some uncertainty regarding this haracter in this species.

31 (30) Oral spines not over 48; eggs not over 85μ..........................
32 (33) Suckers subequal; oral spines interrupted ventrally.......**megacephalu**
33 (32) Acetabulum larger than oral sucker; oral spines not interrupted ventrally..........................
34 (35) Numerous vitelline follicles between ovary and anterior testis..........................**ditremat**
35 (34) No or very few vitelline follicles between ovary and anterior testis
36 (37) Cirrus sac not reaching halfway to ovary; oral spines 36............**sentu**
37 (36) Cirrus sac reaching halfway or more to ovary; oral spines not 36
38 (39) Sucker ratio about 1:2; oral spines 38 to 40..........................**anisotre**
39 (38) Sucker ratio about 1:1.26; oral spines 33 to 34.................. **imparispi**
40 (29) Vitellaria extending some distance along cirrus sac but not reaching acetabulum..........................
41 (42) Length not over 1.9 mm.; eggs about 47μ long.......................... **minutu**
42 (41) Length much over 1.9 mm.; eggs at least 60μ long..........................
43 (44) Acetabulum about twice size of oral sucker..........................**bicoronatu**
44 (43) Acetabulum considerably less than twice size of oral sucker............
45 (48) Oral spines 40 to 42..........................
46 (47) Numerous vitellaria between ovary and anterior testis............**hispidu**
47 (46) Few or no vitellaria between ovary and anterior testis..............**tenu**
48 (45) Oral spines 30 to 36..........................
49 (50) Cirrus sac extending considerably more than halfway to ovary..........................**cloacu**
50 (49) Cirrus sac extending only halfway or less to ovary..........................
51 (52) Cirrus sac S-shaped, wider in anterior half..........................**coryphaen**
52 (51) Cirrus sac almost straight; wider in posterior half..........................
53 (54) Eggs 94 to 109μ long..........................**californicu**
54 (53) Eggs 80μ long..........................**cesticill**

STEPHANOSTOMUM CALIFORNICUM, new species

PLATE 13, FIGURE 13

Description (based on the single specimen collected).—Leng
4.786 mm., greatest width 0.482 mm., near posterior end. O
sucker 0.219 mm., acetabulum 0.321 mm. in transverse diamete
sucker ratio approximately 1:1.47. Oral spines 33, althoug
space at the middorsal line suggests that a thirty-fourth spine h
been lost; spines in anterior row 80 to 90μ long; spines in poster
row 61 to 78μ long. Forebody length 1.255 mm. or slightly l
than one-fourth body length; posttesticular distance 0.606 mm.
approximately one-half length of forebody. Prepharynx 0.5
mm. long; pharynx pyriform, 0.292 mm. long by 0.255 mm. wi
esophagus very short; intestinal bifurcation a short dista
preacetabular; ceca extending close to posterior end of body, pr
ably opening into excretory vesicle.

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[6] Linton (1940) has reported *S. tenue* from six hosts at Woods Hole, but his figures 32 an
with very different extent of the cirrus sac, suggest that he may have dealt with more than
species. Martin (1939) has described the life cycle of this species.

Genital pore median (gp, pl. 13, fig. 13), immediately preacetab-r. Testes (t) tandem in posterior third of body, elongated, arated by a few vitelline follicles; cirrus sac slightly sinuous ending 0.511 mm. posterior to acetabulum or approximately -third distance to ovary. Ovary (ov) elongate, about two-thirds ly length from anterior end; separated from anterior testis by ew vitelline follicles. Vitelline follicles (v) extending anteriorly a point slightly beyond midway between base of cirrus sac and tabulum although not quite so far on one side; not reaching tabulum; not interrupted opposite testes; dorsal, ventral, and eral to ceca; dorsal to testes and ovary but not to the uterus. erus preovarian; metraterm not evident; eggs very large, ovoid, to 109μ by 43 to 58μ.

Host.—*Umbrina roncador* Jordan and Gilbert, yellowfin croaker.

Location.—Intestine.

Holotype.—U.S.N.M. Helm. Coll. No. 37149.

Discussion.—This species differs from most other *Stephanos-num* species in its very large eggs. It seems to be most like *cesticillum* (Molin, 1858) Looss, 1899 and *S. bicoronatum* tossich, 1883) Manter, 1940, which it resembles in number of al spines and extent of vitellaria. *S. bicoronatum* differs in that e oral sucker is only one-half the diameter of the acetabulum, e cirrus sac extends halfway to the ovary, a metraterm is well veloped, and eggs are about 80μ by 50 to 55μ (or 63 to 78μ by to 45μ according to Yamaguti (1938). *S. cesticillum* has eggs μ by 50 to 55μ, an oral sucker only slightly smaller than the etabulum, and a cirrus sac extending more than halfway to the ary, a conspicuous metraterm, and its oral spines are at least ually interrupted ventrally by a spine lacking or by small spines. *S. imparispine* (Linton, 1905) Manter, 1940, has 33 or 34 oral ines but differs in that the vitellaria do not extend so far an-riorly, do not extend between the gonads, and the eggs are only by 40μ in size.

Species that also have large eggs are *S. japonicum* (Yamaguti, 34), which differs in that the vitellaria extend to the acetabulum d there are 46 oral spines; *S. triglae* (Lebour, 1908), differing om *S. californicum* in these same respects; and *S. baccatum* Nicoll, 1907), which has 56 oral spines and tapered eggs.

STEPHANOSTOMUM DENTATUM (Linton, 1900) Manter, 1931

chinostephanus pagrosomi Yamaguti, 1939, p. 221.
tephanostomum pagrosomi (Yamaguti, 1939) Manter, 1947, p. 308.

Host.—*Paralichthys californicus* (Ayres),[7] California halibut.

Location.—Intestine.

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[7] New host record.

Discussion.—The three specimens collected agree with most
the important specific characters of *S. dentatum,* such as: conti
uous distribution of vitellaria to the acetabulum, 48 to 50 or
spines, and contiguous gonads. The forebody is extended, and th
prepharynx is about twice the length of the pharynx or long
than in most specimens of *dentatum.* Sucker ratios are 1:1.3
1:1.37 and 1:1.625 or slightly above the ratio (1:1.22) describe
for *dentatum.* Eggs are 61 to 68μ by 42 to 50μ. These measur
ments approach or reach those given for *S. pagrosomi* (Yamagut
1939), which Manter (1947, p. 308) pointed out was very simila
to *S. dentatum.* It is here considered a synonym.

Genus PLEORCHIS Railliet, 1896

PLEORCHIS CALIFORNIENSIS, new species

PLATE 13, FIGURE 14

Description (based on two mature and five immature spec
mens. Measurements given are for the mature specimens).-
Length 4.901 to 6.435 mm.; width 1.495 to 2.058 mm.; a specime
3.536 mm. long is immature. Oral sucker 0.365 to 0.400 mm.
transverse diameter, somewhat wider than long; acetabulum ci
cular, 0.292 mm. in diameter; sucker ratio 1:0.73 to 0.8. Forebod
0.766 to 1.261 mm. or about one-fifth to one-sixth body lengt
Anterior half of body with large conspicuous spines. A pair
small, rather widely separated eye spots on the dorsal surfa
at, or slightly posterior to, posterior edge of oral sucker. In th
holotype (largest) specimen, the eye spots show signs of bein
lost and the one on the left has disappeared although very fi
black granules occur at its location. Prepharynx 0.043 to 0.24
mm. long, varying with contraction of the forebody; when e
tended it is almost as long as the pharynx; pharynx 0.215 by 0.24
mm. long by 0.219 to 0.234 mm. wide; esophagus a very short na
row tube only 0.021 to 0.029 mm. long; ceca with anteriorly d
rected arms 0.343 to 0.438 mm. long (ace, pl. 13, fig. 14), an
with short lateral branches (ca) arising from outer (or lateral
edges beginning shortly posterior to acetabulum; ceca ending nea
posterior end of body. Testes in dorsoventral pairs arranged
two longitudinal rows, usually 26 or 27 pairs in each row to tot
104 to 108 testes; smallest number observed was 21 and 25 pairs
92 testes. Testes wider than long, close together in the rows. Cirru
sac thin walled, containing a large, ovoid seminal vesicle, more
less clearly divided into a narrowing anterior portion curvin
around the acetabulum and a saclike posterior portion (sv); e
tending well posterior to acetabulum to near the ovary; prostat
cells few; cirrus tubular, unspined. Ovary lobed with short, thic

bes all close together; slightly to right of midline; not far pos-
erior to acetabulum. Mehlis' gland anterior to ovary, between
vary and seminal vesicle; seminal receptacle lacking; uterus short,
reovarian; eggs few, rather thin shelled, variable in size (owing
) abnormal shapes), normal eggs 59 to 67μ by 40 to 45μ. Genital
ore (gp) median, immediately preacetabular. Vitelline follicles
v) close together, extending from slightly posterior to acetabulum
posterior end of body, covering most of the ceca; confluent pos-
erior to testes. Excretory pore terminal; excretory vesicle I-
iaped extending to posterior end of ovary where it flares out
terally to receive the collecting tubes.

Host.—*Cynoscion nobilis* (Ayres), white sea bass.

Location.—Intestine.

Types.—Holotype and paratype, U.S.N.M. Helm. Coll. No. 37148.

Discussion.—The genus *Pleorchis* contains three other species:
. *polyorchis* (Stossich, 1892) Railliet, 1896; *americanus* Lühe,
906; and *sciaenae* Yamaguti, 1938. Manter (1949) has indicated
iat *P. mollis* (Leidy, 1856) Stiles, 1896, almost certainly does not
elong in the genus. *Pleorchis oligorchis* Johnston, 1914, was
ransferred to the genus *Schistorchis* by Yamaguti (1942). *P. cali-
orniensis* differs from all three species in possessing many more
estes (almost twice as many as occur in any of the other species).
t has a much shorter esophagus than does *P. americanus*. The
itellaria do not reach to the acetabulum as they do in the other
hree species. The ovary is more deeply lobed than in *P. sciaenae*.

The family Pleorchidae was named by Poche (1926) to include
leorchis Railliet and *Schistorchis* Lühe, 1906. Cable and Hun-
inen (1942) pointed out that these two genera seemed unrelated
nd that *Pleorchis* should be considered in the family Acantho-
olpidae. *Schistorchis*, with its unspined body and presence of a
eminal receptacle, seems more closely related to *Decemtestis*
'amaguti, 1934. Since *Pleorchis* is the type genus of the Pleor-
hidae, its transfer to the family Acanthocolpidae forces the fam-
y Pleorchidae to become a synonym of Acanthcolpidae. *Pleorchis*,
t least superficially, suggests the subfamily Campulinae (family
'asciolidae). Similarities include such characters as large size,
ody spines, H-shaped ceca, lack of seminal receptacle, I-shaped
xcretory vesicle, preovarian uterus, and extensive vitellaria. The
estes are entirely different and the Campulinae are parasites of
iarine mammals. Probably an important difference is the pres-
nce of very definite eyespots on *Pleorchis*, the cercariae of which
iust therefore be oculate. Eyespots are lacking in all the known
fe cycles of Fasciolidae. The H-shaped ceca may have developed
ndependently in *Pleorchis* and in Campulinae as well as in the
ccacoeliidae.

Family ZOOGONIDAE

Genus DIPLANGUS Linton, 1910

DIPLANGUS TRIRADIATUS, new species

PLATE 13, FIGURES 15, 16

Description (based on nine mature and eight immature spec mens from *Menticirrhus undulatus* and *Roncador stearnsi*).– Length 0.686 to 0.967 mm. One specimen 0.702 mm. in length di not contain eggs although gonads were well developed; anothe 0.686 mm. in length did contain eggs. Body smooth, cylindrica greatest width or thickness near acetabular level, 0.195 to 0.27 mm. Forebody tapering but rounded, hindbody tapering and mor pointed. Acetabulum protrusible and in all specimens greatly ex tended so that the acetabular stalk is almost as long as or eve longer than the hindbody; in one specimen the distance from th acetabulum edge to dorsal wall of body was practically the sam as the total body length. Base of acetabular stalk from one-thir to one-half body length from anterior end of body. The later position of most specimens prevented transverse measurements the suckers. Oral sucker length 0.093 to 0.099 mm., thickness 0.08 to 0.093 mm., width (two specimens) 0.083 to 0.092 mm. Acetabu lum length 0.135 to 0.172 mm., thickness (one specimen) 0.13 mm., width 0.144 to 0.179 mm. Ratio of lengths of oral sucker an acetabulum 1:0.91 to 2. Genital pore (gp, pl. 13, figs. 15, 16 median or submedian, opposite base of pharynx or slightly po terior to pharynx. Short prepharynx present; pharynx often bu not always with a median constriction, 0.054 to 0.063 mm. lon 0.029 to 0.050 mm. wide or thick. Esophagus (e) longer tha pharynx, wide and thin walled. Ceca (ic) sinuous and extendin to level of middle of anterior testis, some distance from posteri end of body, or rarely to posterior edge of posterior testis. Ex cretory pore terminal; excretory vesicle **I**-shaped, extending pa the posterior testis, ending dorsal to anterior testis. Testes glob lar, diagonal, about midway between acetabular stalk and posteri end of body. Genital atrium (ga) a short thin-walled tube. Cirru (cir) thick-walled, bulblike, becoming thin walled just befo joining the atrium; cirrus sac and prostatic vesicle apparently lac ing; seminal vesicle tubular, bipartite with a saclike, thin-walle anterior portion (sv^1) and a swollen **S**- or **V**-shaped tube (sv with cellular walls (fig. 16); vesicle ending near base of acetabula stalk. Ovary globular, slightly anterior to but overlapping th anterior testis, to left of midline. Seminal receptacle (sr) roun well developed, preovarian. Vitellaria (v) in two lateral clum follicles at ovarian level; follicles fairly large, 8 or 9 on each e, often pressed close together. Uterus extending posterior to tes; eggs, more or less collapsed in utero, 27 to 34μ by 13 to 18μ, nost always 32 to 34μ by 13 to 16μ.

About 10 specimens from a related host, *Umbrina roncador*, dif- ed only in being somewhat larger (to 1.802 mm. in length), kers somewhat nearer equal in size, and almost always in having onger space between posterior extent of the uterus and posterior l of body.

Iosts.—*Menticirrhus undulatus* (Girard), California corbina; *ncador stearnsi* (Steindachner), spotfin croaker; *Umbrina ron- lor* Jordan and Gilbert, yellowfin croaker.

Location.—Intestine.

Types.—Holotype and paratype, U.S.N.M. Helm. Coll. No. 37147.

Discussion.—*D. triradiatus* differs from *D. parvus* Manter, 1947, its pointed posterior end, longer hindbody, much smaller ace- ulum and in lack of a prostatic vesicle. It differs from *D. miolec- us* Manter, 1947, in development of the vitellaria, shorter ceca, gonal testes, lack of prostatic vesicle, and smaller eggs. It is bably most similar to *D. paxillus* Linton, 1910. Some apparent erences such as the more posterior genital pore and the sinuous a might be due to the extreme extension of the acetabulum. wever, *D. triradiatus* has diagonal rather than tandem testes, excretory vesicle extends past the posterior testis, a distinct static vesicle is lacking, and the eggs are almost always dis- ctly smaller (usually 32 to 34μ by 13 to 16μ as compared with to 45μ by 14 to 18μ). Eggs of *D. paxillus* were measured in nine cimens from several host species at Tortugas, Fla., and only in (from *Balistes vetula*) were eggs found less than 34μ long.

The name *triradiatus* is suggested by the triradiate appearance en the body by the long acetabular stalk.

Family HAPLOSPLANCHNIDAE

Genus HAPLOSPLANCHNUS Looss, 1902

HAPLOSPLANCHNUS GIRELLAE, new species

PLATE 13, FIGURES 17, 18

Description.—Small, elongate distomes of about equal width and kness; widest and thickest at acetabular level; rounded an- orly but narrowing almost to a point posteriorly. The following asurements are based on seven specimens showing a dorsal ventral view and three specimens showing, as did most of the cimens, a side view (pl. 13, fig. 17). Length 1.073 to 1.569 mm.; th 0.219 to 0.290 mm.; thickness 0.226 to 0.277 mm. Oral sucker (os) wider than long; 0.153 to 0.204 mm. in transvers diameter; 0.153 to 0.197 mm. in depth (dorsoventral). Dorsal wa of oral sucker much thicker than ventral wall; a small papillalik projection often visible on midventral line. Acetabulum, includin aperture, slightly wider than long; 0.157 to 0.219 mm. in transverse diameter or subequal to oral sucker; sucker ratio 1:0.85 t 1.04. Depth of acetabulum, as seen from side view, 0.124 to 0.14 mm. or somewhat less than depth of oral sucker. Forebody 0.299 t 0.431 mm.

Prepharynx very short; pharynx (ph) globular, 0.043 to 0.07 mm. long by 0.048 to 0.068 mm. wide by 0.051 to 0.059 mm. thic Esophagus (e) not clearly demarked from cecum; cecum (ic) extending to a point one-fourth to two-thirds distance from aceta ulum to posterior end of body, usually ending dorsal to testis.

Genital pore median, slightly nearer to oral sucker than t acetabulum, opposite posterior edge of pharynx or slightly po terior to that level. Single testis (t), elongated oval, 0.182 to 0.27 mm. long by 0.116 to 0.138 mm. wide, smooth; located usual somewhat anterior to middle of hindbody; posttesticular space ve long, 0.292 to 0.474 mm., in only one specimen was it shorter tha the forebody. Cirrus a thick-walled tube extending diagonal backward from genital pore, sometimes appearing spherical fro surface view; prostatic vesicle (pv) ovoid to elongate, not appa ent in many specimens; seminal vesicle (sv) a slightly sinuo tube ending dorsal to acetabulum; entering ventral side of pro tatic vesicle slightly posterior to its middle.

Ovary (ov) spherical or ovoid, immediately posterior to aceta ulum or partly dorsal to acetabulum, pretesticular, median submedian, usually slightly dextral. Seminal receptacle spheric or ovoid, largely dorsal and slightly posterior to ovary. Vitelli glands (v) not in definite follicles but in irregular longitudin masses, lateral, usually from level of pharynx to well posteri to testis; always interrupted opposite testis. Anterior extent vitellaria seems to be the anterior border of acetabulum althou large cells in the forebody probably are vitelline cells; the posteri extent varies from one-half to four-fifths distance between tes and posterior end of body. Uterus preovarian, short, dorsal to le half of acetabulum. Eggs (fig. 18) large, few (1 to 7), measuri (uncollapsed) 73 to 80μ by 48 to 53μ. Excretory vesicle forki dorsal to testis.

Host.—*Girella nigricans* (Ayres), common opaleye.

Location.—Intestine.

Number.—Very numerous.

Types.—Holotype and paratype, U.S.N.M. Helm. Coll. No. 371

Discussion.—Of the eight known species of *Haplosplanchnus*, *rellae* is probably most similar to *H. kyphosi* Manter, 1947, and *. obtusus* (Linton, 1910) from Tortugas, Fla. It differs from *. obtusus* in its long posttesticular space, in the spherical shape the seminal receptacle, in lacking distinct vitelline follicles, in e interruption of the vitellaria opposite the testis, and in shape the eggs. It differs from *H. kyphosi* in its unlobed ovary, rela-ely larger acetabulum, elongated testis, interrupted vitellaria, d smaller body size.

Family MONORCHIDAE

Genus PROCTOTREMA Odhner, 1911

PROCTOTREMA LONGICAECUM Manter, 1940

Host.—*Anisotremus davidsonii* (Steindachner),[8] California rgo.

Location.—Intestine.

Number.—Two.

Discussion.—This species is known hitherto from *Anisotremus errruptus* (Gill) from the Galápagos Islands.

Family HEMIURIDAE

Genus APONURUS Looss, 1907

APONURUS TRACHINOTI Manter, 1940

Host.—*Porichthys* sp.[8]

Location.—Stomach.

Discussion.—A single specimen agrees with the description of *trachinoti* except in one respect: the eggs measure 30 to 32μ by rather than 25 by 10μ. Since our specimen is somewhat larger 77 mm. long) and no other differences could be seen, it is felt ew species should not be named. Characteristic features are the pe of the egg (pointed at one end), ceca not reaching the pos-ior end, and the relatively small acetabulum (slightly less than ce the size of the oral sucker).

Genus BRACHADENA Linton, 1910

BRACHADENA PYRIFORMIS Linton, 1910

Hosts.—*Anisotremus davidsonii* (Steindachner),[8] California go; *Porichthys* sp.[9]

Location.—Stomach.

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[8] ew host record.

[9] n the field this host was identified as *Porichthys notatus* Girard. Specimens were not saved ater verification, but it seems probable that the hosts were the locally more common *Porich- myriaster* Hubbs and Schultz, which had been recognized only a short time when this study n progress.

Discussion.—A single specimen was collected from each of t above hosts. Sucker ratio in this species is rather variable. T specimen from *Porichthys* has approximately a 1:2 ratio rath than the more usual 1:2.5 to 3. However, a 1:2 ratio occurs Atlantic specimens from *Ogcocephalus radiatus, Micropogon u dulatus,* and *Calamus bajonado.* This trematode is very comm at Tortugas, Fla., where it has numerous hosts, and it is know also from North Carolina and Massachusetts. This record is t first from the Pacific.

Genus ELYTROPHALLUS Manter, 1940

ELYTROPHALLUS MEXICANUS Manter, 1940

Host.—Paralabrax clathratus (Girard),[10] kelp bass.

Location.—Intestine.

Number.—Two.

Discussion.—This species was found to be common in a varie of fishes of Socorro and Clarion Islands (Mexico) and less comm in the Galápagos Islands (Manter, 1940). The trematode is no mally a stomach parasite.

In the following list of fishes the species are arranged by famili in the sequence followed in the Jordan, Evermann, and Cla checklist (1930).

HOST LIST

CYPRINODONTIDAE: Killifishes

Fundulus parvipinnis parvipinnis Girard, southern California killifish:
    Phyllodistomum sp.

BOTHIDAE: Sinistral Flatfishes

Paralichthys californicus (Ayres), California halibut:
    Bucephalopsis labiatus, new species.
    Stephanostomum denatum (Linton, 1900).
    Immature hemiurid.
    Immature *Distomum fenestratum.*

SERRANIDAE: Sea Basses

Mycteroperca pardalis Gilbert:
    Lepidapedon sp.
Paralabrax clathratus (Girard), kelp bass:
    Elytrophallus mexicanus Manter, 1940.
    Plagioporus isaitschikowi (Layman, 1930).

HAEMULIDAE: Grunts

Anisotremus davidsonii (Steindachner), California sargo:
    Brachadena pyriformis Linton, 1910
    Proctotrema longicaecum Manter, 1940

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[10] New host record.

GIRELLIDAE: Nibblers

- *irella nigricans* (Ayres), common opaleye:
  - *Haplosplanchnus girellae*, new species.
  - *Opechona orientalis* (Layman, 1930).
  - *Opecoelus adsphaericus*, new species.

SCIAENIDAE: Croakers

- *enticirrhus undulatus* (Girard), California corbina:
  - *Diplangus triradiatus*, new species.
- *oncador stearnsi* (Steindachner), spotfin croaker:
  - *Diplangus triradiatus*, new species.
- *mbrina roncador* Jordan and Gilbert, yellowfin croaker:
  - *Diplangus triradiatus*, new species.
  - *Genitocotyle acirrata* Park, 1937.
  - *Pseudopecoelus umbrinae*, new species.
  - *Stephanostomum californicum*, new species.
- *ynoscion nobilis* (Ayres), white sea bass:
  - *Pleorchis californiensis*, new species.

COTTIDAE: Sculpins

- *linocottus analis australis* Hubbs, tide-pool woolly sculpin:
  - *Helicometrina elongata* Noble and Park, 1937.
  - *Opecoelus adsphaericus*, new species.

EMBIOTOCIDAE: Surfperches and Sea perches

- *amalichthys vacca* Girard, pileperch:
  - *Genitocotyle acirrata* Park, 1937.

GOBIIDAE: Gobies

- *illichthys mirabilis* Cooper, mudsucker:
  - Immature hemiurid.

CLINIDAE

- *ibbonsia elegans* (Cooper), ocellated sawfish:
  - *Bucephalus sp.*, immature, encysted.
  - *Helicometrina elongata* Noble and Park, 1937.
- *ibbonsia metzi* Hubbs, weed sawfish:
  - *Helicometrina elongata* Noble and Park, 1937.
  - *Pseudopecoelus gibbonsiae*, new species.

BATRACHOIDIDAE

- *richthys sp.:*
  - *Aponurus trachinoti* Manter, 1940.
  - *Brachadena pyriformis* Linton, 1910.

An examination of the foregoing list reveals a striking degree of
lelity between the digenetic trematodes and their definitive ma-
ne fish hosts in southern California. Only 3 of the 17 species of
genetic trematodes identified in this study have been found to
ansgress family bounds in their definitive hosts. These are
elicometrina elongata, *Genitocotyle acirrata*, and *Opecoelus ad-*
haericus.

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EXPLANATION OF PLATES

All drawings were made from stained permanent mounts i clarite, by aid of a camera lucida. Katharine Hill Paul, scientifi artist in the department of zoology of the University of Illinoi prepared the drawings and arranged the plates.

Symbols Used

a, anus
ac, acetabulum
ace, anterior cecum
ap, acetabular papilla
as, anterior sucker
ca, cecal arm
cir, cirrus
cs, cirrus sac
e, esophagus
es, eye spots
ex, excretory vesicle
ga, genital atrium
gp, genital pore
ic, intestinal cecum
lt, lateral excretory trunk
mt, median excretory trunk
o, egg
ol, oral lip
os, oral sucker
ov, ovary
ph, pharynx
pv, prostatic vesicle
sr, seminal receptacle
sv, seminal vesicle
t, testis
ut, uterus
v, vitellaria
yr, yolk reservoir

Plate 12

1, 2. *Bucephalopsis labiatus*, new species: 1, Holotype as viewed from ve tral surface; 2, lateral view of pharynx and oral lip as seen in paratype individual.

3–5. *Opecoelus adsphaericus*, new species: 3, Holotype as viewed from rig side; 4, acetabulum of a paratype as viewed from lateral surface show papillae, one pair of the lateral papillae not shown; 5, regi of genital atrium showing relations of ducts to other structures.

6, 7. *Pseudopecoelus gibbonsiae*, new species: 6, Holotype in side vie 7, detail showing structures associated with the genital atrium.

8, 9. *Pseudopecoelus umbrinae*, new species: 8, Holotype as viewed fr ventral surface; 9, relations of genital ducts to the genital pore a paratype individual.

Plate 13

10. *Helicometrina elongata* Noble and Park, 1937, viewed from the vent surface. Specimen from intestine of *Clinocottus analis australis*.

11, 12. *Opechona orientalis* (Layman, 1930) Ward and Fillingham, 1934: Entire worm chiefly from ventral view; 12, detail of posterior tremity showing relations of the excretory trunks and vesicle.

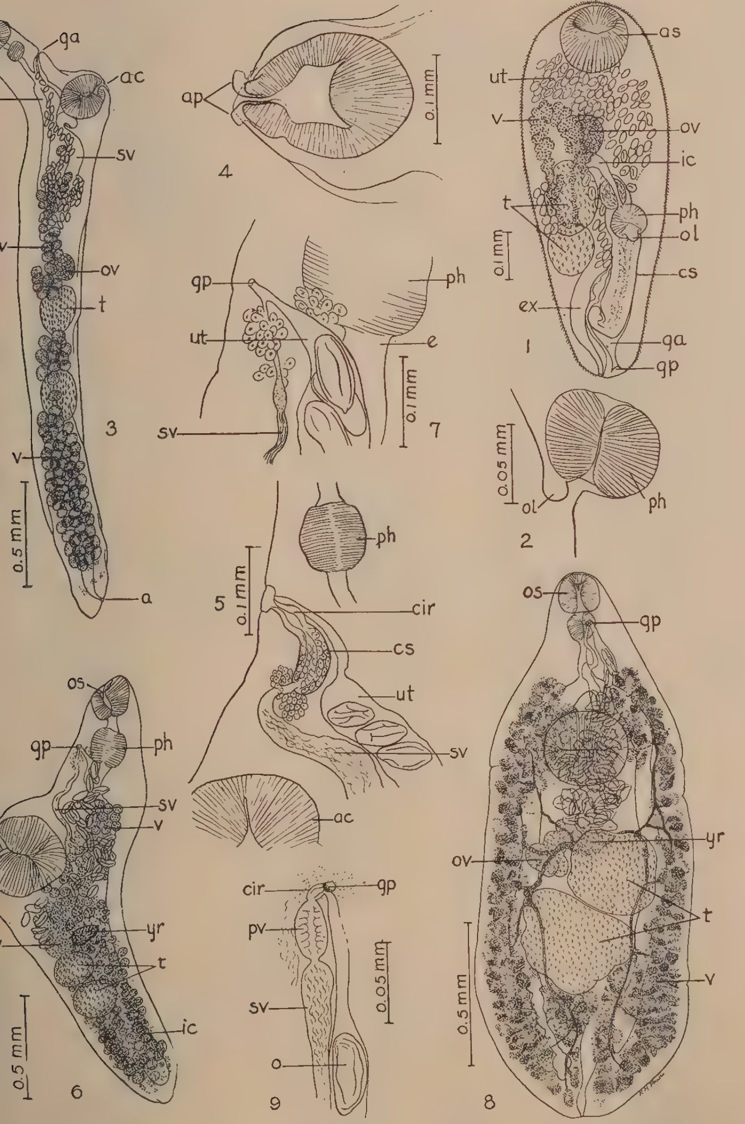
13. *Stephanostomum californicum*, new species: Morphology of holoty

14. *Pleorchis californiensis*, new species: Holotype as viewed from dor surface. Only the dorsal series of testes is shown.

15, 16. *Diplangus triradiatus*, new species: 15, Holotype in side view; 16, A terior extremity of a paratype, showing details of structure.

17, 18. *Haplosplanchnus girellae*, new species: 17, Holotype in lateral vie 18, a single uterine egg.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1950—899135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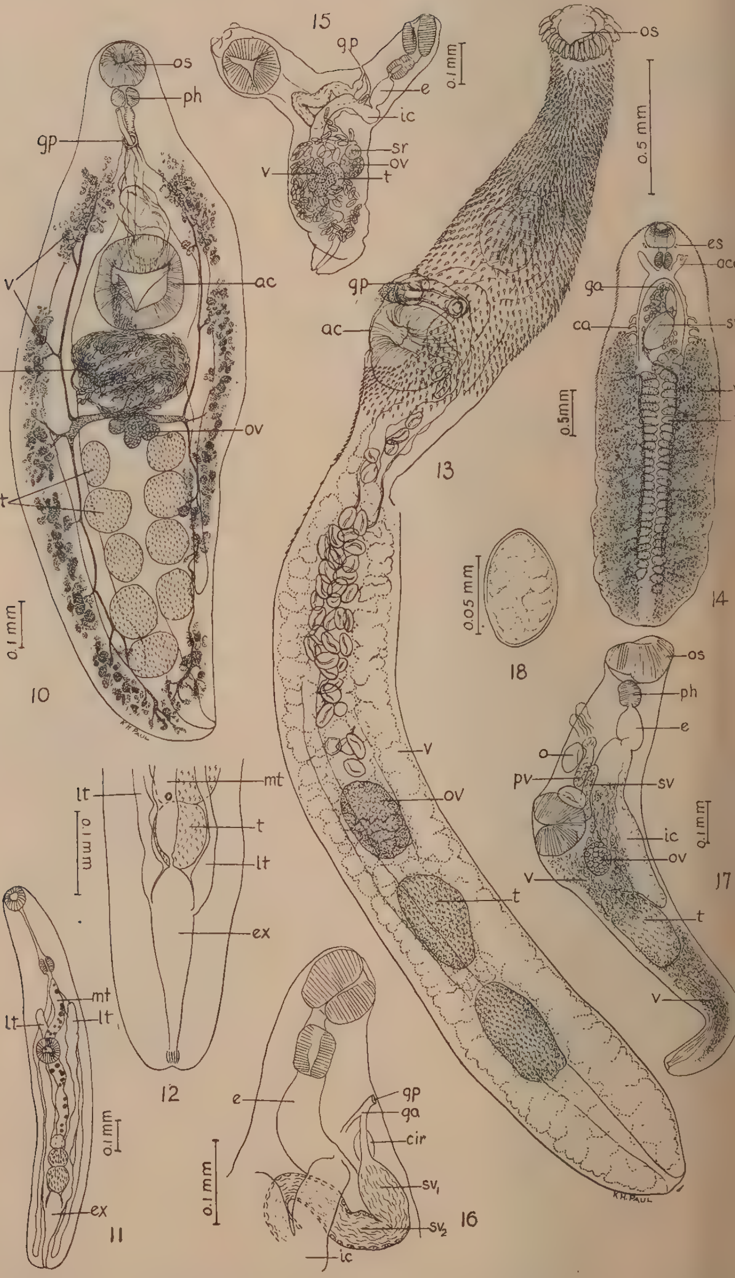
SPECIES OF BUCEPHALOPSIS, OPECOELUS, AND PSEUDOPECOELUS.

FOR EXPLANATION SEE PAGE 340.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SPECIES OF HELICOMETRINA, OPECHONA, STEPHANOSTOMUM, PLEORCHIS
DIPLANGUS, AND HAPLOSPLANCHNUS.

FOR EXPLANATION SEE PAGE 340.

Contribution No. 483

The Wind-driven Circulation in Ocean Basins of Various Sha

By W. H. MUNK[1] and G. F. CARRIER[2]

(Manuscript received 6 March 1950)

Abstract

The ocean circulation induced by zonal winds has been derived for a triangular ocean basin. The method, which involves the "boundary layer" technique, can be extended to a more general wind system, and to ocean basins of arbitrary shape provided the boundaries are not too irregular. In low and mid-latitudes the principal effect of an inclination, Θ, of the western boundary relative to a north-south direction is to widen the western current (Gulf Stream) by the factor $(\sec \Theta)^{1/3}$ and to reduce the current intensity by a similar factor. A variation in the circulation pattern associated with the variation in the value of the lateral eddy viscosity is noted.

Introduction

The wind-driven circulation in a rectangular ocean basin has been discussed by HIDAKA (1949) and by one of us.[3] The actual shapes of the North Atlantic and North Pacific Oceans deviate greatly from that of a rectangle, but resemble somewhat more closely triangular or semicircular basins, the two cases considered in this paper. The solutions obtained indicate the effect on western currents, such as the Gulf Stream and Kuroshio, of the orientation and curvature of the coast line.

The equation of mass transport and boundary conditions

The stream lines of mass transport, ψ, obey the equation (WOC)

$$\left(A\Delta^4 - \beta\frac{\partial}{\partial x}\right)\psi = -\operatorname{curl}_z\tau, \qquad (1)$$

where A is the kinematic eddy viscosity
taining to lateral stresses, $\nabla^4 = \partial^4/\partial x$
$+ 2\partial^4/\partial x^2\partial y^2 + \partial^4/\partial y^4$ is the biharmonic
rator,

$$\beta = \frac{df}{dy} = \frac{2\Omega}{R}\cos\varphi$$

is the rate of change northward (positive
twice the vertical component of the ea
angular velocity Ω, f the Coriolis paramete
the earth's radius, φ latitude, and $\operatorname{curl}_z\tau$
vertical component of the wind stress
The positive x-axis extends eastward.

Equation (1) is essentially an integr
version of the vorticity equation, and expr
a balance between three torques: the la
stress torque, the planetary vorticity, and
wind curl. The equation has been der
(WOC) by integrating the equations of
tion (including horizontal and vertical
bulent stresses) from the surface to s
depth where the motion and horizontal
sure gradients essentially vanish, and then
forming the curl operation. Observations
shown that the velocity of the wind-dr
currents at depths of one or two thou
meters equals but a small fraction of the
face velocity.

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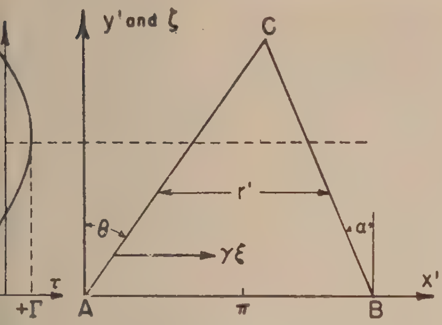
[1] Institute of Geophysics and Scripps Institution of Oceanography, University of California. Contribution from the Scripps Institution of Oceanography, New Series, No. 483. This work has been supported by the Office of Naval Research.

[2] Department of Applied Mathematics, Brown University, Providence, Rhode Island.

[3] W. H. MUNK (1950), *On the Wind-driven Ocean Circulation*, published in the Journal of Meteorology. This article will hereafter be referred to by the symbol (WOC).



Dimensions of triangular ocean basin. The wind
: varies from $-\Gamma$ at $y' = 0$ ($\varphi = 15°$ N), to $+\Gamma$
$= \pi$ ($\varphi = 50°$ N). A unit distance equals 35°
e/π, or 1032 km. In these units r' is the latitudinal
of the ocean basin, and $\gamma\xi$ the distance from the
western boundary.

το considerable simplifications result from
ing with the vertically integrated equa-
In the first place, we can examine the
of a baroclinic ocean without having to
y the vertical distribution of density
urrent; secondly, only the vertical stresses
upper boundaries need to be specified,
hose can be computed from the known
field over the ocean.

: a wind system we set

$$\tau_x = -\Gamma \cos ny, \quad \tau_y = 0 \tag{3}$$

g maximum easterlies at $y = 0$ (latitude
and maximum westerlies at $y = \pi/n$ (see
). The method can easily be extended to
bitrary distribution of zonal winds, and
: certain conditions to a general wind
field (WOC).
ume a triangular ocean basin with the
nsions shown in fig. 1. For the boundary
tions along AC and BC we choose

$$\psi_{\text{bdry}} = 0, \quad (\partial \psi / \partial \nu)_{\text{bdry}} = 0 \tag{4a, b}$$

: ν is normal to the boundary. Along AB

$$\psi_{\text{bdry}} = 0, \quad (\partial^2 \psi / \partial \nu^2)_{\text{bdry}} = 0. \tag{5a, b}$$

tions (4a) and (5a) state that the bound-
ABCA is a stream line. According to
no slippage takes place along the land
dary ACB, whereas according to (5b) no
l shear exists along the sea boundary
The boundary conditions are equivalent to those imposed on a rigid plate clamped along the coast line ACB and supported along the latitude line AB (WOC).

Solution by boundary layer method

Introducing the non-dimensional parameters $\psi' = \beta\psi/\Gamma$, $r' = nr$, $x' = nx$, $y' = ny$, $n^4 \nabla'^4 = \nabla^4$, and writing $k^3 = \beta/A$, equation (1) becomes

$$\left(\gamma^3 \nabla'^4 - \frac{\partial}{\partial x'}\right) \psi' = \sin y', \tag{6}$$

where $\gamma = n/k$ is the ratio of the wind wavenumber n to the "Coriolis friction" wavenumber k. The distance π/n between the easterlies and maximum westerlies is roughly 3500 km; it will be shown that

$$\frac{2\pi (\sec \Theta)^{4/3}}{\sqrt{3}\, k}$$

is roughly the latitudinal width of the western currents, say 350 km. Setting $\Theta = 60°$ for the Pacific gives $\gamma \approx .035$.

Inspection of equation (6) now shows that the problem belongs in the "boundary layer" category. The leading term (which contains higher order derivatives than all other terms) has a coefficient $\gamma^3 \ll 1$. The asymptotic solution of equation (6) (i.e., the solution which becomes more and more exact as $\gamma^3 \to 0$) can therefore be anticipated to give a good approximation to the exact flow except in the vicinity of the boundary intersections.

The conventional procedure for obtaining this solution is the following. We find a particular solution of equation (6) by neglecting the term containing γ^3. Such a solution is

$$\psi'^C = -x' \sin y' + d \sin y'. \tag{7}$$

In order to obtain the homogeneous boundary layer solutions which lead to the determination of d and the satisfaction of the boundary conditions, it is convenient to introduce the following coordinate system (fig. 1):

$$\xi = \frac{x'}{\gamma} - \frac{\zeta}{\gamma} \tan \Theta, \quad \zeta = y', \tag{8}$$

so that

$$\psi'^C = (-\gamma\xi - \zeta \tan \Theta + d) \sin \zeta \tag{9}$$

and

$$\frac{\partial}{\partial x'} = \frac{1}{\gamma}\frac{\partial}{\partial \xi}, \frac{\partial}{\partial y'} = -\frac{1}{\gamma}\Phi \tan \Theta \frac{\partial}{\partial \xi} + \frac{\partial}{\partial \zeta}. \tag{10}$$

In equation (10)

$$\Phi(\varphi) = 1 - \frac{\zeta}{\gamma}\frac{d\gamma}{d\zeta} = 1 - \frac{1}{3}(\varphi - \varphi_0) \tan \varphi \tag{11}$$

is a correction involving the *second* derivative of the Coriolis parameter. Here φ_0 is the latitude at which $\gamma = \zeta = 0$, about 15° N. The correction is small at low latitudes and amounts to 25 per cent at 50° latitude.

It is seen that variations in the y-direction involve ζ explicitly as well as implicitly through ξ. Since $\gamma \ll 1$, it follows that only the latter need be considered, so that

$$\nabla'^4 \approx \gamma^{\;4} p^{-3} \frac{\partial^4}{\partial \xi^4} \tag{12}$$

where

$$p^{-3} = (1 + \Phi^2 \tan^2 \Theta)^2. \tag{13}$$

With these substitutions the asymptotic form of the homogeneous equation becomes

$$\left(\frac{\partial^4}{\partial \xi^4} - p^3 \frac{\partial}{\partial \xi}\right) \psi' = 0 \tag{14}$$

with the solution $\psi' = \psi'^W + \psi'^E$, where

$$\psi'^W = \frac{1}{2}(a + ib)\, e^{-\frac{1}{2}(1+\sqrt{3}\, i) p\xi} \sin \zeta +$$
$$- \frac{1}{2}(a - ib)\, e^{-\frac{1}{2}(1-\sqrt{3}\, i) p\xi} \sin \zeta, \tag{15}$$

$$\psi'^E = c e^{-p(r'/\gamma - \xi)} \sin \zeta. \tag{16}$$

It is seen that ψ'^W decreases exponentially with distance from the western boundary and $\psi'^C + \psi'^W$ is therefore the western boundary solution; similiarly $\psi'^C + \psi'^E$ is the eastern boundary solution; whereas ψ'^C is the solution in the central portion of the ocean.

The boundary conditions (5) along AB are already satisfied. The constants a, b, c and d can be evaluated from the boundary conditions along ABCA. Along the western boundary $\xi = 0$, and equations (4 a, b) give

$$-\zeta \tan \Theta + d + a = 0, \quad 2\gamma/p + a - \sqrt{3}\, b = 0.$$

Along the eastern boundary $\xi = r'/\gamma$, v
$r' = r_0'(1 - \zeta/\pi)$ is the (non-dimensi
latitudinal width of the ocean, and r
(tan Θ + tan α) the width at $\zeta = 0$. The
ern boundary conditions give

$$-r' - \zeta \tan \Theta + d + c = 0, \quad -\gamma/p +$$

The boundary conditions can be combin
yield

$$a = -r'(1 - \varepsilon), \quad c = r'\varepsilon,$$
$$\sqrt{3}\, b = -r'(1 - 3\varepsilon), \quad d = r'(1 - \varepsilon) + \zeta \text{ t}$$

where $\varepsilon = \gamma/pr'$ is a small quantity.
approximation involved in the non-h
geneous term (7) can now be estimate
performing the operation indicated in
tion (6) on ψ'^C:

$$\left(\gamma^3 \Delta'^4 - \frac{\partial}{\partial x'}\right) \psi'^C = \sin y' \,[1 - \gamma^3 (d -$$

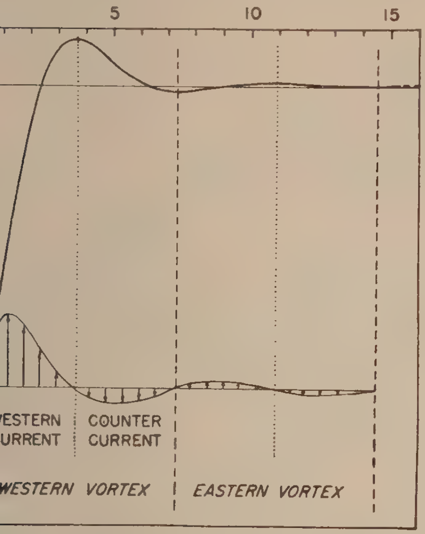
The exact solution requires that the righ
equal sin y'. Since $d - x' = r'(1 - \varepsilon) - \gamma\xi$
at most, the neglected term is less than
that is less than 1 per cent.

The solution becomes

$$\psi' = r' \sin \zeta \Bigg[-\frac{2}{\sqrt{3}}\left(1 - \frac{3}{2}\varepsilon\right) e^{-\frac{1}{2}p\xi}$$
$$\left(\frac{\sqrt{3}}{2} p\xi + \frac{\sqrt{3}}{2}\varepsilon - \frac{\pi}{6}\right) + 1 -$$
$$- \varepsilon\left(p\xi - e^{p\xi - 1/\varepsilon} - 1\right)\Bigg].$$

For north-south boundaries, $\Theta = 0$, p
and the equation reduces to the rectan
case discussed in (WOC). The first term
bracket gives the variation of ψ' with x
the western boundary, as shown in
It indicates a series of exponentially "dam
boundary vortices, with a strong north-flo
current and countercurrent in the w
vortex, both of latitudinal width $2\pi/\sqrt{}$
The principal effect of the inclined w
coast line is to widen the western c
(measured normal to the boundary) b
factor

$$p^{-1} \cos \Theta \approx (\sec \Theta)^{1/3}$$



East-west variation of ψ' near the western bound- r an infinitely wide ocean [equation (18) with The arrows indicate the direction and intensity of ng-shore component of the current. Compare with Figures 4 to 6.

o reduce the current intensity by a similar . The approximation refers to low lati- in high latitudes the modification associ- with an inclination of the coast line is ed, or even reversed. The total transport ns approximately the same. The inclination of the eastern boundary is important only insofar as it involves the width r of the oceans.

Circulation of the Pacific Ocean

Fig. 3 shows a chart of the Pacific Ocean on which north-south and west-east distances have been preserved. The basin north of 15° N is approximated by an isosceles triangle with a base of 13 units and altitude of 4 units (1 unit = 1032 km, see fig. 1). *A* rectangle is also drawn, which has the proper width at a latitude of 32.5° N midway between the easterly and westerly winds.

Figs. 4—6 show the computed stream lines in the triangular and rectangular ocean basins for the following numerical values of the parameters:

	Fig. 4	Fig. 5	Fig. 6
Shape of basin	triangle	rectangle	triangle
A in cm² sec^{-1}	$2.5\cdot10^7$	$2.5\cdot10^7$	10^8
π/n	35° lat.	35° lat.	35° lat.
At 30° N latitude:			
k in cm^{-1}	$2.0\cdot10^{-7}$	$2.0\cdot10^{-7}$	$1.25\cdot10^{-7}$
γ	.040	0.040	.064
p	.445	1.00	.445
$\frac{2\pi}{\sqrt{3pk}}$ in km	410	182	650
$\frac{2\pi}{\sqrt{3pk}}\cos\Theta$ in km	215	182	341

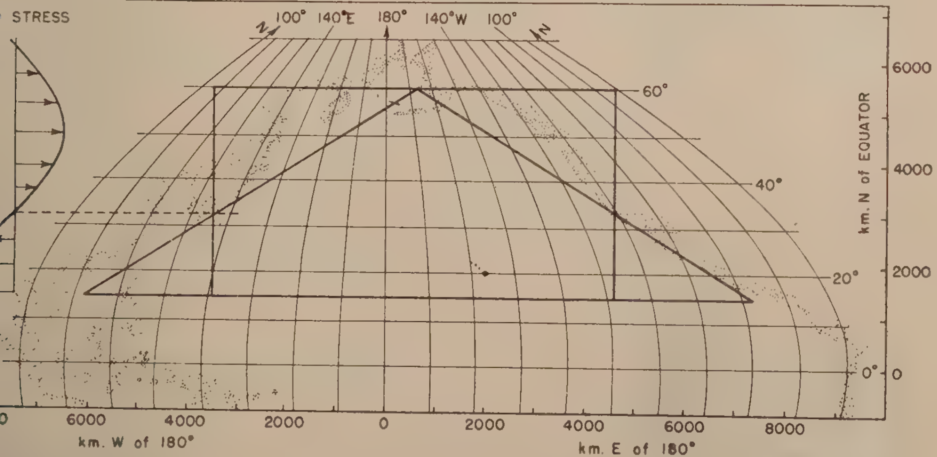


Chart of Pacific Ocean. The outer scales give distances in km west or east of 180°, and north of equator. culation induced by a zonal wind stress distribution (shown to the left of the figure) has been computed for the cases of the triangular and rectangular oceans drawn in the figure.

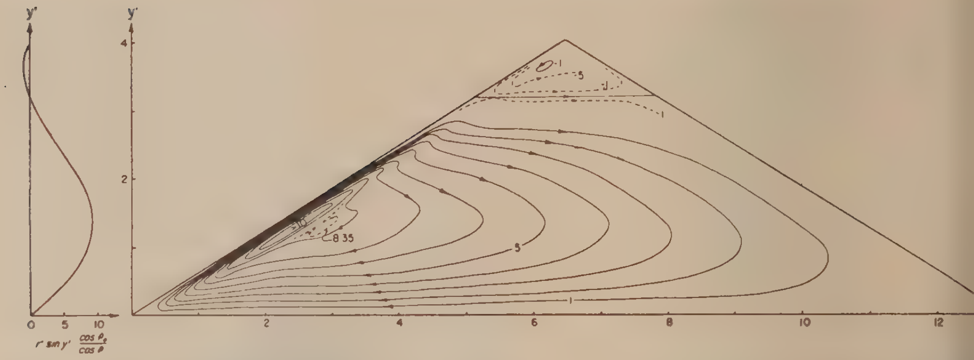


Fig. 4. Computed transport stream lines in the triangular ocean basin for $A = 2.5 \cdot 10^7$ cm^2 sec^{-1}. The represent equal values of $(\beta_0/\Gamma)\psi$. The curve to the left represents the variation of ψ with latitude. Unit dist along the x- and y-axis equal 1032 km. The section between $x = 1.5$ and $x = 4.0$, $y = 0.5$ and $y = 2$ been redrawn on an enlarged scale in Figure 8.

The last two lines give the latitudinal and actual widths of the western current and countercurrent at the latitude 30°N where these currents attain their maximum intensity.

The stream lines are drawn[1] for equal values of

$$\frac{\beta_0}{\Gamma}\psi = \frac{\cos \varphi_0}{\cos \varphi} r' \sin \zeta \, [f(p\xi, \varepsilon)] \qquad (19)$$

where β_0 is the value of β at $y' = 0$. The function in the bracket is the one in equation (18).

The expression preceding the bracket function of y only, and shown to the le figs 4 and 5. In the case of the triang ocean this function vanishes at latitudes 15 50° N and 60° N, and accordingly di the circulation into an anticyclonic an cyclonic gyre. These gyres have been na the subtropical and subpolar gyres (W and correspond roughly to the regions o subtropical anticyclones and of the cycl storms, respectively. In the case of the

---

[1] The approximations involved break down near the northern vertex of the triangle where the 2 boundary strips overlap. In this region the stream lines have been estimated. Because the real and abstracted boun differ greatly in this small region, it seems hardly w while to devise special methods to compute the position of the theoretical stream lines.

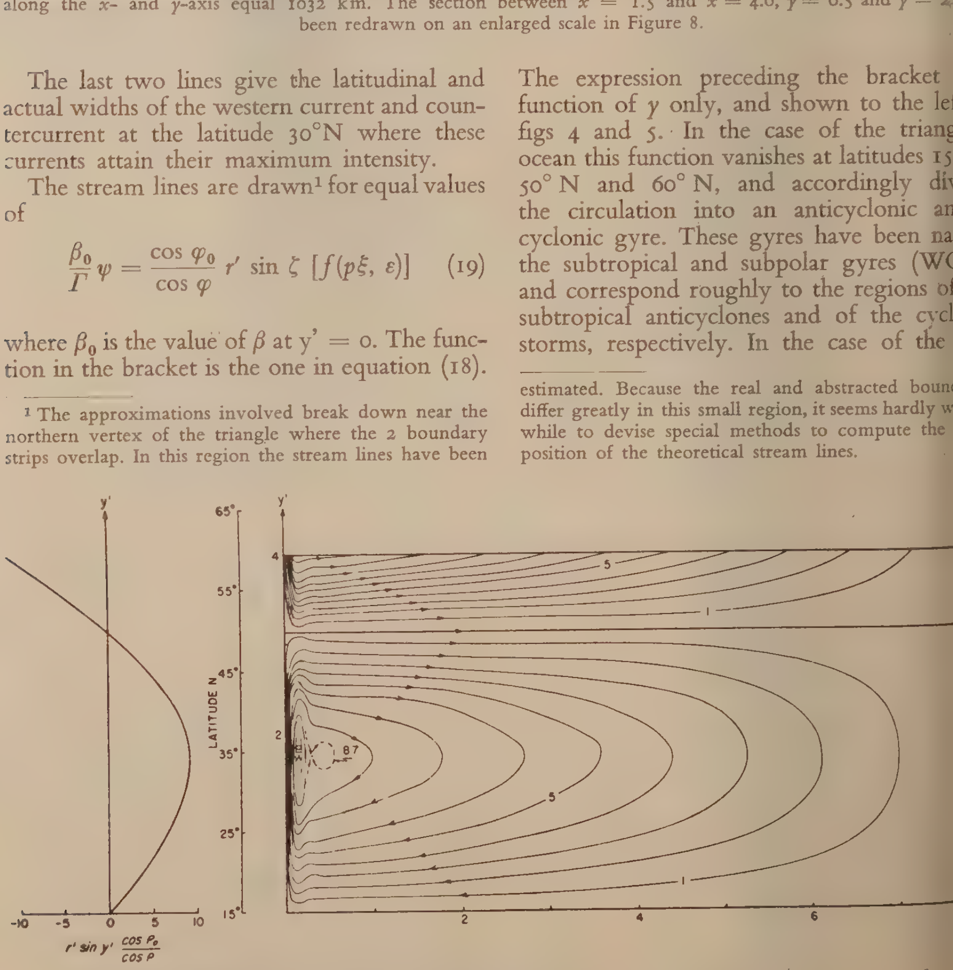


Fig. 5. Computed transport streamlines in the rectangular ocean basin for $A = 2.5 \cdot 10^7$ cm^2 sec^{-1}.

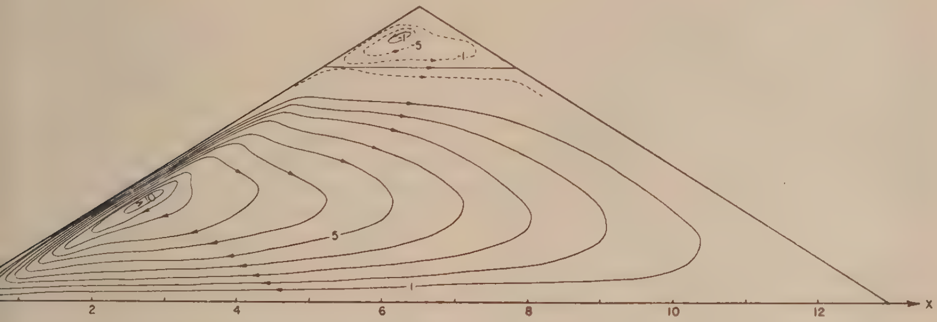


Fig. 6. Computed transport stream lines in the triangular ocean basin for $A = 10^8$ cm^2 sec^{-1}.

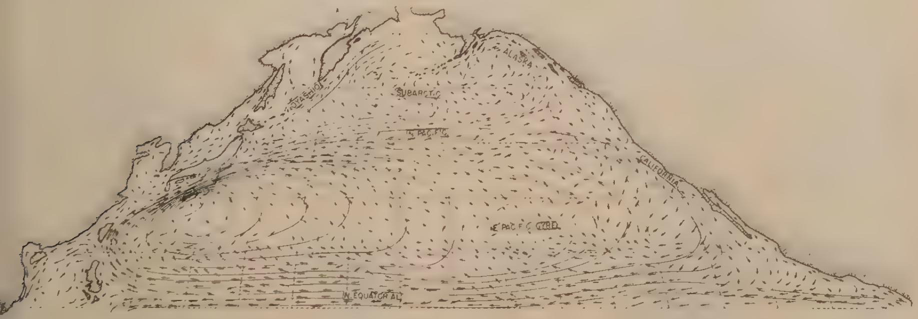
ar ocean only part of the subpolar gyre uded.

location and intensity of the gyres on and 6 compares favorably with oceano-ic measurements, as presented in fig. 7. that the maximum transport of the n (Kuroshio) current takes place at latitude; that the ratio of mass transport Kuroshio Current to that of the Oyashio nt is of the order of 10:1. The eastern gyre and the California Current are sult of local meridional winds (WOC) re therefore not present in our model nal winds.

pancy between observed and computed ort

nputations based on the available wind nd the best available information concerning the relationship between wind speed at anemometer level and the stress exerted on the sea surface gives $\Gamma = 0.65$ dynes cm^{-2}. (WOC) Setting $\beta_0 = 2.2 \cdot 10^{-13}$ cm^{-1} sec^{-1} one finds that each unit of $\beta_0\, \psi/\Gamma$ as drawn on figs. 4—6 represents a transport of $3 \cdot 10^{12}$ *g* sec^{-1}, or 3 million metric tons sec^{-1}. This is one half the contour interval in fig. 7. We conclude that the computed *pattern* of water transport resembles the observed pattern quite closely, whereas the computed *quantity* of transport is about half the observed quantity.

This discrepancy cannot be ascribed to the value of the eddy viscosity, for, according to equation (18), the transport is almost independent of A. Nor can the discrepancy be ascribed to our assumption of no slippage against the western boundary. Taking the extreme case of *free slippage* against the western



Transport chart of the North Pacific as derived from oceanographic observations. Transport between stream lines are six million metric tons sec^{-1}. The stream lines are based on Fig. 205 of Sverdrup et), the arrows on the "Weltkarte zur Übersicht der Meereströmungen", Tafel 22, Deutsche Seewarte, *Ann. d. Hydrogr. u. Mar. Meteor.*, 1943. The projection is the same as the one in Figure 3.

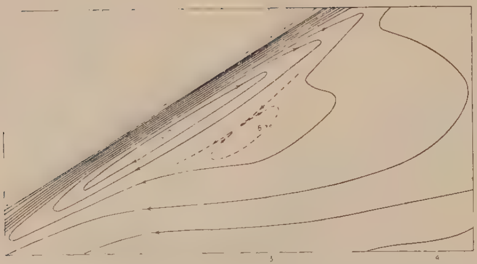


Fig. 8. Computed Pacific "Sargasso Sea" circulation in the triangular ocean basin for $A = 2.5 \cdot 10^7$ cm² sec⁻¹. This figure is an enlargement of the south-west portion of figure 4.

boundary by replacing boundary condition (4 b) with $\partial^2\psi/\partial v^2 = 0$ at $\xi = 0$, yields $b \approx +r'/\sqrt{3}$ (instead of $b \approx -r'/\sqrt{3}$), and

$$\psi'_{\max} = 1.30\, r' \sin\zeta \quad \text{at} \quad p\xi = 4\pi/3\sqrt{3}$$

instead of

$$\psi'_{\max} = 1.17\, r' \sin\zeta \quad \text{at} \quad p\xi = 2\pi/\sqrt{3}.$$

Thus with maximum velocity occurring directly against the boundary the western current has two-thirds its former width, and the transport is 20 per cent higher.

A more important modification may be related to the effect of the earth's rotation on lateral stress. Following the customary procedure we have, from analogy with the Navier-Stokes equations, introduced lateral stress into the integrated equations of motion through the term $A\nabla^2\mathbf{M}$. (WOC) Since the Navier-Stokes equations were derived for a resting coordinate system it would seem appropriate to replace the *relative* mass transport M by the absolute value $M + \mathbf{i}\,\Omega Rh \cos\varphi$, where $\mathbf{i}$ is the unit vector pointing eastward, and h the effective depth of the current. Performing the curl operation[1] one obtains an additional term

$$A\frac{\partial^3}{\partial y^3}(\Omega Rh \cos\varphi) = \frac{A\Omega h}{R^2}\sin\varphi$$

to be added to the wind curl on the right side of equation (1). Setting $A = 2.5 \cdot 10^7$ cm² sec⁻¹, $\varphi = 30°$, $h = 10^5$ cm, gives $2 \cdot 10^{-9} g$ sec⁻² compared to a wind curl of about 9 · 1c sec⁻². The effect would be to strengthe transport in the subtropical gyre by a 25 per cent, to weaken the transport i subpolar gyre, and to displace the boun between the gyres northward.

The physical basis of this modific forms the substance of Rossby's (1936) cussion concerning the merits of Ta vorticity-transport theory and Prandtl's mentum-transport theory. If angular mo tum is to be conserved, then any merid interchange of eddies must induce a re current setting eastward at high latitudes westward at low latitudes.

The discrepancy may also be ascribed underestimate of the surface stress for a wind speed, especially at wind speeds of fort four or less (WOC).

These remarks apply particularly to western currents. In the case of the equatorial current (of which only h shown on figs. 4—6), the equatorial cou current, and the south equatorial cu Sverdrup (1947) and Reid (1948) have tained satisfactory agreement between transport computed from the wind and that computed from oceanographi servations.

The western boundary vortices (Sar Sea) and the value of A

An interesting feature is the double v system near the western boundary on f and 5, which is shown on an enlarged sca fig. 8. In the case of fig. 6 the small ea vortex is absent, but its effect can sti noticed by the bulging of the stream

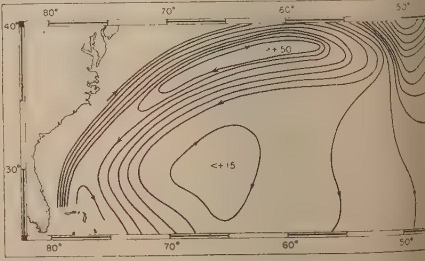


Fig. 9. Idealized topography of the sea level of the Atlantic Ocean according to Defant (1941). Th are dynamic centimeters.

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[1] Here again we employ a plane coordinate system. In spherical coordinates the modification is several times larger. We hope to return to this problem in greater detail when considering a basin on a spherical earth.

er the eastern vortex will or will not sent depends only on the width of the and the value of the eddy viscosity, as seen from an inspection of equation (18). rve in Fig. 2 represents a graph of the n f($p\xi$) in the bracket of equation (18) infinitely wide ocean ($\varepsilon = 0$). The n oscillates about the value of 1, and, speaking, the vortex system extends to , though the amplitudes of the vortices exponentially with distance from the boundary. In the case of an ocean n-dimensional) width r' the function es not about the horizontal line $f(p\,\xi) = 1$, out the line $f(p\xi) = 1 - \varepsilon p\xi$. The vortex exists only if the slope of the m in the bracket of equation (18) at the e $(p\xi)_m = 14\pi/\sqrt{3} = 8.45$, where it its third maximum, exceeds the slope the asymptotic line; that is, if

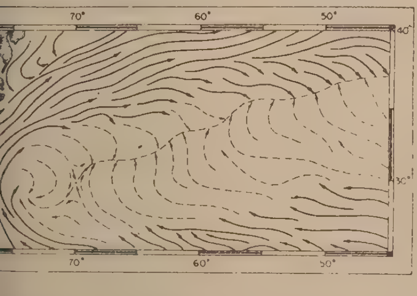
$$\frac{2}{\sqrt{3}}\, e^{-\frac{1}{2}(p\xi)_m} \sin\left[\frac{\sqrt{3}}{2}(p\xi)_m\right] = 0.015.$$

rresponding conditions on γ and A are:

$$\gamma < 0.015\, pr',\ \ A < \frac{(0.015\, pr')^3 \beta}{n^3}.$$

Pacific at latitude 30° N, $p = .445$, $r' =$ $\beta = 2 \cdot 10^{-13}$ cm^{-1} sec^{-1}, $\pi/n = 3\,900$ which gives $A < 8.25 \cdot 10^7$ cm^2 sec^{-1}. e Atlantic at the same latitude, $\Theta \approx 50°$, 25, $r' = 6.0$, and $A < 7.8 \cdot 10^7$ cm^{2}sec^{-1} r for the eastern vortex to exist.

erms of the dynamic topography of surface the double vortex system re- s two humps in the sea surface, the hump being much larger than the eastern hump (fig. 8). The two humps are separated by a trough running parallel to the western current with a saddle point directly between the humps. Observations in the Pacific Ocean are inconclusive with respect to the existence of the eastern hump. The corresponding area in the Atlantic, the Sargasso Sea, is one of the most intensely studied areas in the world, but even so the conclusions are uncertain. DEFANT'S (1941) analysis of the dynamic topography based on observations from the *Meteor* expedition, and previous expeditions, is reproduced in fig. 9. It shows a small hump in the Bermuda area, but according to Defant (personal communication) the data was not quite convincing in this respect. At Defant's suggestion FELBER (1934) had previously analyzed the extensive observational material based on surface drifts of vessels, and his stream lines show a saddle point southwest of Bermuda throughout the year. His figure for April is reproduced in fig. 10.



Stream lines in the north-west Atlantic from the e drift of ships, according to Felber (1934).

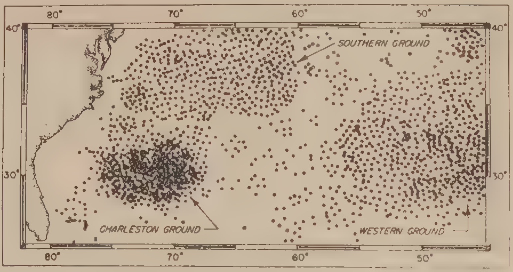


Fig. 11. Distribution of the sperm whale based on log-book records dating from 1761—1920 (according to TOWNSEND 1935). Each point represents the position of a whale ship on a day when one or more whales were taken.

Defant's and Felber's analyses are consistent with respect to the existence of a saddle point at about 70° west, 30° north, but they differ regarding the Gulf Stream countercurrent. This discrepancy has to do with the different methods of averaging employed by the two authors. The large number of observations[1] collected since Defant summarized the data in 1941 have made increasingly clear the variability of the circulation in the Bermuda area,

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[1] We are indebted to C. O'D. Iselin, F. Fuglister, and A. Worthington of the Woods Hole Oceanographic Institute for having made these observations available to us.

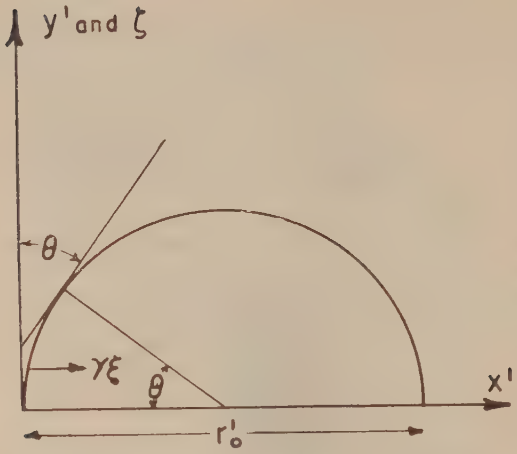

Fig. 12. Dimensions of semi-circular ocean basin.

and the shifting in position from season to season, even from week to week, of the Gulf Stream and related features (Iselin and Fuglister, 1948). Defant's analysis is based on synoptic profiles, each of which reveals a countercurrent seaward of the Gulf Stream, occurring however at different locations for different cruises. Felber's averaging at fixed geographic location would naturally tend to obscure secondary features adjacent to strong but wandering primary features. The differences are somewhat similar to the differences between synoptic weather maps and climatic charts.

No suitable methods have yet been developed for combining results from different cruises to bring out the existence of secondary features such as the countercurrent and the eastern vortex. For this reason observations collected since 1941 have not added materially to our understanding of the Sargasso Sea circulation, but most of these observations indicate a north-flowing current west of Bermuda. A curious clustering in the distribution of sperm whales may perhaps be interpreted as evidence for the existence of the two vortices and the trough. Each point in fig. 11 represents the position of a whale ship on a day when one or more whales were taken, according to logbook records dating from 1761 to 1920 (Townsend, 1935). Relatively few points are found in the region of the trough, yet there appear to have been no reasons for whaling ships to avoid this region.
troughs, according to Felber's presentatio
regions of convergence. In such region
concentration of nutrients is small, and
may expect a relatively small concentrati
plankton, and of sperm whales which
on plankton. It is not impossible that the
vortices represent optimum conditions fo
existence of plankton, these being the
where freely floating organisms woul
main for the longest time under uniforr
vironmental conditions.

In a comparison of figs. 5—8 one
keep in mind that fig. 8 applies to the P
Ocean, whereas figs. 5—7 apply to the Atl
As a whole, the evidence, though far
conclusive, seems to support the existen
the eastern vortex, and would therefore
cate that the lateral eddy viscosity in
region is less than $7.8 \cdot 10^7$ cm² sec⁻¹.

The effect of curvature in the bounda

It has been stated previously that the p
method can be extended to an ocean ba
arbitrary shape provided the boundari
not too irregular. To express this in q
tative form, consider a semi-circular ba
diameter (not radius) r'_0 (fig. 12).
coordinate system we choose

$$\xi = \frac{x'}{\gamma} - \frac{r'_0}{2\gamma}(1 - \cos \Theta), \quad \zeta = \frac{r'_0}{2} \sin$$

where, as previously, $\gamma\xi$ is the non-dim
nal distance from the western boundary
inclination relative to a north-south dire
and r'_0 is the width of the basin at γ
Differentiation leads to the same transf
tion as given by (10) except that Θ no
pends on ζ. Neglecting variations in
obtain

$$\nabla^2 = \frac{1}{\gamma^3}\left(\sec^2 \Theta \frac{\partial^2}{\partial \xi^2} - \frac{2\gamma}{r'_0} \sec^3 \Theta \frac{\partial^2}{\partial \xi \partial \zeta} +\right.$$

The second term is a correction for the
ture of the coastline. This correction is
provided the radius of curvature

$$\frac{1}{2} r'_0 \gg \gamma \sec \Theta.$$

As an extreme example of irregular b
aries consider the sharp change in the o

f the eastern seaboard between Jackson-
Florida, and Savannah, Georgia. Setting
0.04 would require the radius of curva-
o be large compared to .04 units of
ce, or 40 km. The actual radius of cur-
: is 160 km.

usions

: present method appears to be suitable
numerical computation of the gross
es in the ocean circulation, taking into
nt the outlines of the actual boundaries.
simple models discussed here give an indication of the results of such a computation. Changes in the orientation of the coast line will lead to a widening or narrowing of the western current, but the general features should be more or less the same, irrespective of the boundaries. This is in agreement with the fact that the general circulation is similar in the various oceans, whereas the ocean boundaries are not.

Acknowledgement

We are indebted to Mr P. Osborn for his assistance in preparing the figures.

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MINIMUM EVAPORATION FROM WATER SURFACES

N. W. Cummings

(Contribution from the Scripps Institution of Oceanography, New Series, No. 484)

> Editor's note: During editing of this paper, which is published posthumously, questions arose regarding notation and subscripts of some of the symbols. While it is hoped that they are now correct, it seems appropriate to inform readers that there may still be inconsistencies, particularly in making direct comparisons with Cummings' 1946 paper. George F. McEwen, one-time co-worker and long-time friend of the author, has agreed to prepare a closure on the author's behalf if discussion should make this appropriate.

Abstract--It is shown that if the water surfaces in a series are in the steady state, and subjected to the same incoming rate of energy supply, but differing wind, one of them will have a smaller evaporation rate than those under either greater or less wind. This fact is utilized to point out serious limitations on pans as indicators of lake evaporation. The conclusion so obtained is supported by available data.

Introduction--YOUNG [1947, 1948] and his associates have rendered an important and valuable vice in compiling the large mass of evaporation data (including many pan records) recently lished by the California Department of Public Works. But to say that the compilation has value ot equivalent, by any means, to saying that the pans themselves have value as indicators of true e evaporation. Fortunately, Young included a number of records applying to actual lakes, and se undoubtedly have great value.

Recognition of the existence of a temperature at which evaporation during a given time inter- is a minimum, was stimulated by an examination of Young's work.

There appears to be no historical evidence to show that when any of the commonly used pans, h the possible exception of the one bearing the name of the Bureau of Plant Industry, were in- duced, anything in the nature of design was attempted, apart from obvious structural consid- tions. Nevertheless, some of the pans might conceivably turn out by good fortune alone, to e genuine indicator value, although the probabilities are against such an outcome.

In order to appraise any pan records completely, we must take account of the relation between variability of pan-to-lake coefficients and that of lake evaporations. There are two ways in ch this relation can be investigated. The first is by direct observations, and the second by in- ence from fundamental generalizations, but in view of the extreme scarcity of reliable direct ervations, the more fundamental attack has obvious advantages. It will therefore be presented st, and available data bearing directly on the question will be briefly summarized later. The dom components of turbulent motion are supposed to integrate to zero, so that only average ocities are considered.

Energy components--The fundamental generalizations reveal several energy components MMINGS, 1946], all of which can, in general, vary, but the variations are not entirely free m constraints imposed by the first and second laws of thermodynamics and the properties of and of water vapor. For examining those variations of the dissipative energy rates which are sible under the constraints, we may write the following equations for the discharge from unit a of a water surface in unit time,

$$Q_L = g_L\,(\theta_o - \theta_2) \quad \ldots\ldots\ldots\ldots \quad (1a)$$

$$Q_S = g_S\,(\phi_o - \phi_2) \quad \ldots\ldots\ldots\ldots \quad (1b)$$

$$B = \alpha(T_w^4 - T_a^4) \quad \ldots\ldots\ldots\ldots \quad (1c)$$

The left-hand members are the evaporative, convective, and radiative components, while the are functions of wind. Some writers have regarded each g as proportional to the wind velocity, but since in the Epstein solution of the basic differential equation, it does not come out exactly t way, the more general form is retained. The binomials ($\theta_o - \theta_2$) and ($\phi_o - \phi_2$) are measures o the differences in respect to vapor pressure and temperature between air and water, while T_w the Kelvin temperature of the water surface, T_a a temperature representative of sky conditions and α the Stefan constant.

It is an erroneous, but unfortunately a very common assumption, that since g_L is an increa ing function of wind, if we increase wind, we necessarily increase Q_L, whereas in actual fact, w may do nothing of the kind. Some writers forget all about the decrease in ($\theta_o - \theta_2$) that may ac company an increase in g_L. Without further information we have no means of knowing whether the overall effect will be an increase or a decrease in Q_L, and accordingly, as a step toward pr curing the needed additional information, a hypothetical experiment will be described.

Simultaneous conditions at different water bodies--Let two similar water bodies, X and Y, warmer than wet bulb, be provided, and let conditions be so controlled that both are in a steady state, and subject to the same T_a conditions. Let the sum of the dissipative energy components be the same for both bodies, as also the wet and dry bulb, while the wind velocity is greater for X than for Y. That is, let

$$[Q_L + Q_S + B]_X = [Q_L + Q_S + B]_Y \ldots\ldots\ldots\ldots\ldots\ldots (2$$

and

$$[g_L]_X > [g_L]_Y \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2$$

At any height greater than a few millimeters, $g_L = g_S$, and may accordingly be factored ou the sum of the right hand members of (1a) and (1b). If then, the wind velocity increases as we from Y to X, at least one of the three binomials must decrease. But since the wet and dry bul remain constant, each binomial decreases with water-surface temperature so that as the wind i creases, the water-surface temperature decreases. This temperature relation in its proper qu titative aspect, is a necessary and sufficient condition for meeting the designated experimental quirements. Temperature can accordingly (under the constraints) be regarded as a measure o wind, so that if we take full account of the effect of changes in temperature, we do not in additio need to take explicit account of changes in wind. That is, wind is implicitly taken care of when deal properly with temperature, or the curve between evaporation rate and temperature, is two dimensional. While this conclusion may come as a surprise to persons unaccustomed to think terms of any definite dissipation of energy, its truth can be easily seen by remembering that by division, the g's, which are the only terms containing wind, can be eliminated from (1a) and (1b [CUMMINGS, 1946]. Although in doing so, we diminish by one, the number of equations at our disposal, the conservation of energy enables us to restore the loss. At the temperature of the bulb, it is easily shown in various ways that the relation between wind and temperature become indeterminate. From an observational standpoint, this relation becomes less and less definite, as the wet bulb is approached.

If now in (1a) and (1b), we decrease g by going from X to Y, and at the same time increase the binomials, what (under the constraints) do we do to Q? In particular, do we do the same thi to both Q's, or do we increase one and decrease the other?

Second law of thermodynamics--A well-known principle which helps provide the easy answe is the second law of thermodynamics. Thus if X is slightly cooler than the air, while Y is sligl warmer, then according to the second law, Q_S is negative for X and positive for Y so that it increases as we go from X to Y. But B certainly increases as we pass from X to Y so that Q_L m decrease if the sum of all three is to remain constant. Thus, under these conditions, Q_L and Q vary oppositely. A commonly held view, on the contrary, implies that they vary in the same di tion.

Condition under which evaporation is independent of surface temperature--Differentiating with respect to T_w, [see (6b)] and taking account of the relation between temperature on the one hand, and rate of change of pressure of saturated vapor with temperature, on the other, suggest that the curve between evaporation rate and temperature, may be convex toward the temperatu axis, since the derivatives of g_L and θ_o have opposite signs. Does its slope ever pass through zero and change sign? To answer this we can replace our two experimental water surfaces by whole series which may be called a reference series, and we can write the basic energy equati [CUMMINGS, 1946]

$$E\ \mathrm{cm} = [(I - B - S - C)\ \mathrm{cal/cm^2}]/[(L\ \mathrm{cal/gm})(1\ \mathrm{gm/cm^3})(1 + R)] \ldots\ldots ($$

ere E is the evaporation during any specified time interval, I and B are the corresponding ra-
ation terms, S the heat accumulated in the water during the time interval, C a general correction,
d L the heat of vaporization. For convenience let $h = I - B_o$ since $S = 0$ in the steady state, and
is negligible for most lakes; and let $B = B_o + b$, with B_o independent of such changes in T_w as
cur; $R = Q_S/Q_L$. Generalizing further to permit the arbitrary variation of h, gives the mathe-
atical relation

$$DE = (dE/dT_w)DT_w + (dE/dh)Dh \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

It is a matter of considerable importance to keep the meanings of the symbols clear. The
t member of (4) is the total differential when wind, temperature and radiation all change, while
e first term on the right, is that part of the differential not due to changes in h; that is, it cor-
sponds to those changes in E that would occur, if there were no changes in h, but were changes
wind and temperature. This means that, subject to the conditions for (1a), dE/dT_w is a total
rivative, because in the steady state h is constant when the sum of the dissipative components
es not vary. Consequently wind is not neglected in (4). The temperature referred to in con-
ction with equations (4) through (8) is that of the water surface.

From (3) and (4), it is obvious that if $dE/dT_w = 0$,

$$DE = (dE/dh)DH = [Dh]/[L(1 + R)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

that, under such conditions, evaporation may be expressed as a function of h and R alone. From
) or (1a), we obtain, for the derivative dE/dT_w, either

$$E/dT_w = (\partial E/\partial b)(db/dT_w) + (\partial E/\partial R)(dR/dT_w) = -[(db/dT_w)/(1 + R) + h(dR/dT_w)/(1 + R)^2]/L \quad (6a)$$

r

$$dE/dT_w = (\partial E/\partial T_w) + (\partial E/\partial g_L)(dg_L/dT_w)$$

$$= g_L(d\theta/dT_w) + (\theta)(dg_L/dT_w)/L\,, \qquad \theta = \theta_o - \theta_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (6b)$$

ut (6a) is more convenient because it easily shows the derivative to be zero when

$$-(db/dT_w)(1 + R) = h(dR/dT_w) \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Failure to distinguish between dE/dT_w and $\partial E/\partial T_w$, undoubtedly accounts for some of the
roneous comments that have been made regarding the application of the energy equations. If h
constant, R and the variable part of B in (3), could, under any particular conditions except T_w
uals wet bulb, be replaced by functions of the single variable T_w, so that there is no inconsist-
ıcy between the total derivative property of dE/dT_w, and the two dimensional character of the
ırve between evaporation and temperature.

The numerical value, (0.5 cal/cm^2) per hour per degree, of the derivative db/dT_w, is ob-
ined by differentiating the Stefan fourth power equation for radiation, since $dT_a/dT_w = 0$, and a
asonable value for h is (14 cal/cm^2) per hour, giving from (7),

$$dR/dT_w = -0.05 \text{ deg}^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

There can be no doubt as to the existence of a negative rate of change of R with water surface
mperature under certain conditions. If (7) does not explain its relation to evaporation, what
es? In the differentiating, time is, of course, not regarded as a variable. Instead, we are pass-
g instantaneously from lake to lake or from pan to pan in a reference series.

No conflict with turbulence theory--It is obvious from (6a) that under the assumed experi-
ental conditions, the evaporation rate may increase, decrease, or (over an infinitesimal range)
main constant while the wind increases, and this conclusion is in no way incompatible with tur-
ılence theory. Thus, to say that Q_L remains constant, is merely to set $(\theta_o - \theta_2)$ proportional
the reciprocal of g_L, which is entirely permissible under turbulence theory, and merely pro-
des an answer to a question with which turbulence theory has thus far not concerned itself.

Heat storage--In the theoretical treatment as thus far presented, perfect consistency with
ısic postulates takes us through (7), but we cannot proceed farther without making certain judg-
ents as to magnitudes, and without mentioning the relation between incoming and outgoing energy,
hich involves the heat accumulated in the water as designated by S. But the aim which stimulated
e writing of the paper in the first place, was to find some basis for judging the value of a pan as

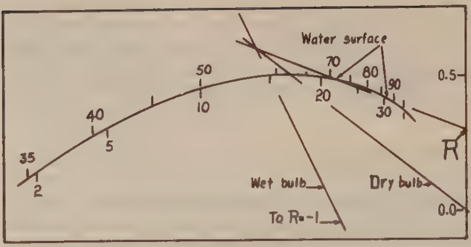

Fig. 1--Alignment diagram for R, the ratio of convection to evaporation; when the rate of change of R with water surface temperature is about -0.05 per degree, the evaporation is independent of water surface temperature, and therefore of wind

a lake indicator. How can the neglect of S as has been done here, interfere with the attainm of that aim? Over an annual cycle S is known be almost exactly zero for many lakes, and ov any interval of time for which the commonly u pans could be imagined to have any usefulness it is small by comparison with evaporation. M over, it is a time change, whereas the aim of paper is to investigate the behavior of water bodies under differing average conditions, par ularly with respect to air movement. There i reason why (I - S) cannot be constant over any segment of a reference series and a bad pan c not be made good by the removal of such restr tions.

Minimum evaporation--As any actual lake may be a member of a reference series, and a (6b) and the relation $(dE/dT_w)(dT_w/dg_L)$ joint make dE/dg_L and dE/dT_w vanish together, (8) tells us the condition under which the particular lake in question would have a smaller evaporation than any other lake receiving the same energ from sun and sky, but subject to greater or less wind, and (6a) tells us the conditions under wh a small change in wind produces a negligible change in evaporation rate.

An examination of the alignment diagram [CUMMINGS, 1930] of Figure 1, shows that the ra of change of R with surface temperature has the value required by (8) under conditions frequen met. This means that evaporation from a lake can, during an important part of the time, be re garded as independent of wind, and an earlier paper has pointed out that it is nearly independen of humidity [CUMMINGS, 1929]. For any given combination of wet and dry bulb and incoming r diation, the slightly negative rate of change of R with water surface temperature corresponds t that particular water surface temperature that yields a minimum evaporation and a near maxi mum discharge of sensible heat by convection. Above that temperature, the increasing driving tendency for water vapor prevails, and below, the decrease in the driving tendency for sensible heat prevails, reducing that tendency to zero when the water surface and dry bulb have the sam temperature. To state the facts roughly but briefly, the wind does so much cooling, that it can only a little evaporating at the temperature of minimum evaporation. In other words, the wind blows away sensible heat instead of water vapor, because R is so large, say 30 per cent.

Lakes different from pans--In this respect a lake is notably different from any of the commonly used pans, because none of these pan temperatures combines with wet and dry bulb tempe atures in such a way as to give a slightly negative rate of change of R with water surface tempe ature. Nevertheless, it is reasonable to suppose that a pan can be so designed as to give these desired temperature combinations. We consequently have no reason to expect a pan to be a goo indicator of lake evaporation unless it is specifically designed with this end in view, and with a understanding of the fact that wind and humidity exert only a minor influence on evaporation fro a lake.

Examination of data--(The abbreviation, WB pan, will refer to the Weather Bureau pan that has long been in use.) No satisfactory observational check on the foregoing conclusion is at pr sent possible, because there never have been adequate parallel series of pans and lakes. Neve theless, some little work of this kind has been done, so that, by improvising, we can draw some inferences, albeit rather tenuous ones. The real question is not whether a pan can or cannot yi information, but rather how does the pan compare with other means in respect to the yielding o information about lakes?

This question has been investigated for several localities chiefly by the aid of two methods of calculation. The first is the simple proportion: the evaporation from lake X, is to the evapo ration from Lake Elsinore in California, as the pyrheliometer reading near X, is to the pyrheli ometer reading at Riverside, a short distance from Lake Elsinore. The second assumes that when reduced to the same units, the difference in evaporation at any two points is equal to the d ference in radiation divided by (1 + R), according to (5). For lakes, R appears to be fairly clos to 0.2, while for WB pans it fluctuates about zero. When the time intervals are the same, radia tion in cal/cm^2 may be reduced to inches of evaporation by dividing by 2.54 cm/in × 585 cal/cm = 1480 $(cal/cm^2)/in$. The only case in which there seemed to be any reason for supposing that pan-to-lake coefficient could yield a smaller error, was the Ft. Collins, Colorado data for whic e Lincoln, Nebraska pyrheliometer had to be used. But by using the WB pans at Ft. Collins and ncoln (not in the pan-to-lake coefficient manner, but merely for the purpose of reducing the ncoln radiation to the substantially lower Ft. Collins value), a highly satisfactory result was ob- ned. If other records had been available, even this use of the WB pan could probably have been oided [HAND, 1937; ROHWER, 1931].

If this supposition is correct, the absence of any need for the pan would have been more clear- demonstrated. Although the Lincoln and Ft. Collins pans appear to have acted in a mutually nsistent manner, Young's compilation provides ample evidence that WB pans are frequently er- tic, so that we cannot depend on the good fortune that existed in this particular case.

Over large areas, the lake evaporation may, with a remarkably small error, be treated as iform. Thus for six non-desert lakes in California reported by YOUNG [1948], the average loss 54.3 in/yr, and the average departure from this average is 2.75 inches or five per cent. For o desert lakes, the average is 72.0 in/yr and the departure is about the same. The difference tween desert and non-desert lakes is $72.0 - 54.3 \approx 18$ inches or about 35 per cent, whereas some the pans have a ratio of 2 to 1.

In view of these relations, it is difficult to imagine circumstances in which the WB pan can nder any real assistance in estimating lake losses, when the person making the estimate has y choice whatever as to the kind of instrument that is to yield the basic information. The data e less complete for other commonly used pans, but we have no reason to suppose that any of em, with the possible exception of the one bearing the name of the Bureau of Plant Industry, have y indicator value when that term is interpreted in the comparative manner previously suggested.

Pan design--It is difficult to understand how the WB pan can be reconciled with scientific eteorology and hydrology. The design of this pan could be improved with ease. Thermal insula- n might constitute a substantial improvement even when the pan is used in the ordinary way. It quite possible that obstructing the opening would improve the design by raising the average temp- ature and throwing the high temperature toward early morning so as to yield more favorable mbinations with wet and dry bulb thermometer readings. Screening devised by YOUNG [1937, 15] does something of this kind, although a continuous obstruction around the edge of the opening uld probably have important advantages. The objective in designing a pan should be to make . (3) when applied to the pan, correspond in magnitude, term by term, with the same equation en applied to a lake. Although this objective can probably never be exactly reached, commonly ed pans can be improved with respect to it.

Of course, when estimates are quickly needed at places where no records of any kind are ailable except WB pan readings, it may sometimes be necessary to use those records, particu- rly when, as at Ft. Collins, there is reason to suspect some purely local condition which makes e radiation depart from the general trend. These emergencies cannot, however, be regarded as eason for continuing the use of such pans.

San Diego County lakes-- It would be helpful if the engineer who made the evaporation com- tations for the SAN DIEGO COUNTY INVESTIGATION [1935], would explain how he found enough ergy to account for the high losses reported. Table A-2 and page 165 show 72 inches for Cuya- ca, 63 inches for El Capitan and San Vicente, and 60 inches for Mission Gorge, notwithstanding ly 56.2 inches for Lake Elsinore [YOUNG, 1948, p. 99]. Because of proximity to the coast, one ght reasonably expect the radiation in San Diego County to be less than in Riverside County, the ation of Lake Elsinore. This difference is shown by a pyrheliometer reading of 365 $(\mathrm{cal/cm^2})/$ y at La Jolla in San Diego County, as compared to 424 $(\mathrm{cal/cm^2})$/day at Riverside [HAND, 1937, 436], near Lake Elsinore. The published evaporations appear to be based on floating pans.

Presumably, a more reliable figure would be obtained for Mission Gorge, San Vicente, and Capitan, by assuming a radiation equal to the mean of Riverside and La Jolla, that is, 390 $\mathrm{l/cm^2}$)/day. Subtracting this from Riverside, dividing by 1.2×1480 $(\mathrm{cal/cm^2})$/inch and multi- ing by 365 to reduce to an annual basis, gives seven inches less for the San Diego lakes than for sinore, or 49 inches per year. This is most likely a lower limit, since the back radiation is obably less for the San Diego lakes than for Elsinore. But if instead of using the entire reduc- n of seven inches per year, we use half that figure, we shall obtain 53 inches per year, which is, hout doubt, a very close approximation to the actual loss.

Until reliable measurements of radiation at Cuyamaca become available, there is no way of imating the evaporation from that lake that would be any better than a rough guess as to what e radiation might be. Nevertheless, such a guess, if made intelligently, may not be as far wrong as might at first appear, because the radiation data [HAND, 1937], show a degree of unformity th must be gratifying to anyone confronted by the practical need for some kind of an estimate of eva oration. This uniformity, in the light of the facts embodied in (5), and the fairly close approxima tions underlying (8), no doubt accounts for the samll variation among the lakes reported by Young

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The Occasional Papers, publication of which was begun in 1931, serve as a medium for original papers based principally upon the collections of the Museum. The papers are issued separately to libraries and specialists, and, when a sufficient number of pages have been printed to make a volume, a title page, table of contents, and index are supplied to libraries and individuals on the mailing list for the entire series.

The Miscellaneous Publications, which include papers on field and museum techniques, monographic studies, and other contributions not within the scope of the Occasional Papers, are published separately, and as it is not intended they will be grouped into volumes, each number has a title page and, when necessary, a table of contents.

MISCELLANEOUS PUBLICATIONS
MUSEUM OF ZOOLOGY, UNIVERSITY OF MICHIGAN, NO. 78

STUDIES OF CYPRINODONT FISHES. XX. A NEW SUBFAMILY FROM GUATEMALA, WITH CTENOID SCALES AND A UNILATERAL PECTORAL CLASPER

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MAP PAGE

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STUDIES OF CYPRINODONT FISHES. XX. A NEW SUBFAMILY FROM GUATEMALA, WITH CTENOID SCALES AND A UNILATERAL PECTORAL CLASPER[1]

INTRODUCTION

BIZARRE novelties continue to appear in the Cyprinodontes (Microcyprini). As late as 1940 a new family was discovered in India (Kulkarni, 1940; Hubbs, 1941). The latest such discovery to come to my attention is that of a genus, from the interior of Guatemala, which is referable to the American viviparous family Poeciliidae but is so unique in three respects as to call for its segregation in a separate subfamily.

XENODEXIINAE, NEW SUBFAMILY

Type genus, *Xenodexia,* described below.

The Xenodexiinae are unique among fishes in the extreme specialization of one pectoral fin (Hubbs and Hubbs, 1945: 294–95). In the adult male the axillary region of the right pectoral fin (Pl. II, Figs. 2–3) is spectacularly modified into a very complex structure, presumably of some copulatory function, whereas the left fin remains unmodified. In some ways this pectoral clasper is comparable with the pelvic claspers (myxopterygia) of the Elasmobranchii. Some flatfishes (Heterosomata) have one pectoral fin, that of the blind side, reduced in size and in number of rays, or even completely obsolete (Hubbs and Hubbs, 1945: 254–63), but in no known group are the pectoral fins modified differentially in basic structure for clasping, or for any other function, and in none, with the possible exception of the remarkable Phallostethidae, are the pectoral girdles so modified. If Bailey (1936: 475) was correct in interpreting the toxactinium in some Phallostethidae and the pulvinulars in others as homologs of a pectoral girdle structure (the alternative suggested homology with detached lower pectoral rays seems wholly improbable), that group would also show an asymmetrical secondary-sexual modification of the pectoral limb, for the priapial structures mentioned are unpaired. No close relationship, however, can be postulated between the Phallostethidae and the Xenodexiinae or any other division of the Cyprinodontes (Myers, 1928; Hubbs, 1944: 74–75, with other references).

The Xenodexiinae are unique among the Cyprinodontes in the ctenoid structure of the scales (Pl. III). This discovery, though surprising, is in harmony with the varied evidence that the Cyprinodontes are more advanced in teleostean evolution than are the Haplomi and that they are closely related to the Acanthopterygii and possibly even derivable from that group (Regan, 1911: 321; Hubbs, 1920: 67, 1924: 3–4, 1944: 75; Myers, 1928: 3–4; Gregory, 1933: 216–20; Boldyreff, 1935; Lagler, 1947: 160). Particularly unexpected is the discovery of ctenii on a fish that appears to represent a terminal modification of the specialized viviparous family Poeciliidae. There is some evidence that many, possibly all, ''lower'' teleosts with cycloid scales had ancestors with ctenoid scales. This view, which I have held for some years, has been mentioned briefly by Lagler (1947: 159).

---

[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 485.

Since it is hardly conceivable that the typically ctenoid scale of *Xenodexia* was independently evolved,[2] we are confronted with a series of alternative explanations for the retention of ctenii in this genus: (1) One alternative is that *Xenodexia* is the sole known surviving genus of a line that was derived from an ancestral cyprinodont with ctenoid scales. This line might have branched from a very primitive cyprinodont, on which assumption the ctenii may have been lost but once in the Cyprinodontes; or from an ancestral poeciliid, on which hypothesis one would infer repeated loss of the teeth on the scales, since other families, including the more primitive Cyprinodontidae, also lack ctenii. The fact that *Xenodexia* is highly specialized in some respects does not argue strongly against this view, for, as I have repeatedly pointed out, primitive and specialized characters are very commonly if not usually combined; that is, existing relicts of primitive groups are usually highly specialized in some respects, and many highly specialized types retain some primitive characters. I disfavor this first alternative, however, because there is strong support for the view that *Xenodexia* is a highly modified poeciliid.

If *Xenodexia* is a specialized member of the Poeciliidae, two further alternatives remain: (2) The ctenii may have been retained throughout the complex ancestry of the genus but lost in every other line of cyprinodont evolution. This idea overtaxes the concept of parallel degenerative evolution, especially in view of the indications that the whole group, the Poeciliidae in particular, is relatively recent and actively proliferating. (3) Finally, *Xenodexia*, as a highly modified poeciliid, may have regained a very specialized structure that was long lost in the phylogeny of the group. The total evidence seems to support this explanation. The loss might have been only in the phenotypic expression of the character, as the result of a prolonged suppression of the effects of genes that nevertheless persisted. Such apparent exceptions to the law of irreversible evolution do seem to occur. To cite a parallel case, the development of teeth in only one living anuran is most plausibly attributed to the renewed expression of the causative genetic mechanism (Cornman, 1943). Another case, involving the abnormal appearance in the modern dog of the long-lost third upper molar, has been cited by Wood and Wood (1933).

---

[2] The possibility of independent evolution of ctenii in *Xenodexia*, at first given some credence, before the structures were studied in detail, was presented briefly by Lagler (1947: 160).

Whether it be assumed that *Xenodexia* originated from near the root of the order, or from near the base of the family, or from a specialized branch of the Poeciliidae, the asymmetrical modification of the pectoral fin and the ctenoid structure of the scales provide ample need for recognizing it as the sole known representative of a distinct group, which I interpret as of subfamily rank.

The third character of the Xenodexiinae, much less distinctive, is the broad extension of the coelom into the urosome over the entire base of the anal fin (Pl. IV), causing the very short interhemals of the female to project into the body cavity, far removed from the vertebral column. The corresponding vertebrae in both sexes carry ribs (and, apparently in part also, parapophyses), but in the female they do not bear hemal spines.

The backward extension of precaudal-type vertebrae into the urosome in *Xenodexia* may be considered merely a further step in a process already begun in all Poeciliidae and carried far in some genera. In *Alfaro* and *Furcipenis* the air bladder penetrates about as far into the urosome, but in these genera the female retains hemal spines in the position of the gonapophyses of the male (Howell Rivero and Hubbs, 1936).

Despite its ctenoid scales and other distinctive features, there can be no hesitation in referring *Xenodexia* to the Cyprinodontes. Every other observable feature is in harmony with this reference.

The pertinence of the Xenodexiinae to the Poeciliidae seems almost equally certain, for the fundamental characters are those of that family. Like other poeciliids *Xenodexia* is viviparous, with greatly reduced fecundity. As in all other members of the family the ovary is a single, thin-walled sac. As in all other genera the anal fin of the male is elaborately modified into an intromittent organ (Pl. I), the gonopodium, comprising rays 3 to 5 and supported by a complex suspensorium (Pl. IV, Figs. 1–2), in the basic structure highly distinctive of the family. The main osteological features of the gonopodial suspensorium in *Xenodexia,* as in other poeciliids, are the extreme specialization of the interhemals and the profound modification of the connected vertebrae (Howell Rivero and Hubbs, 1936). The anterior interhemals, from the second to the fifth or sixth, are much enlarged, thickened, and consolidated to comprise the rodlike compound interhemal, which with its investing muscles projects into the body cavity. The posterior interhemals, much less modified but considerably clumped, are connected with the vertebral column by two or more curved or angulated bony spines. These unique structures are almost certainly to be homologized with hemal spines, though they are often unrepresented or incompletely represented in the female. In fact, none of the many modifications of the gonopodial suspensorium are evident in the female or in the young.

The xenodexiines further agree with the Poeciliidae in two nonsexual features, recently determined, by which all poeciliids differ from the oviparous Cyprinodontes: (1) The third anal ray, reaching nearly to the pointed tip of the fin, is unbranched. This ray is branched in all oviparous forms, except in some young and in the species with a low, anteriorly rounded anal fin. (2) In addition to the lateral-line organs typical of the whole group (those on the axial scale row of the urosome and those on the next higher row on the trunk), neuromasts or pit organs, one of which is shown on Plate III, occur in the following places: on the second scale row above the series along the ventral edge of the caudal peduncle, along the first row of large scales above the anal base, and on the breast. In the oviparous cyprinodonts neuromasts do not occur in those regions, except in the very few species in which the organs follow all scale rows. Incidentally, these characters permit the identification to family of series of American cyprinodonts that are represented only by immature specimens.

The two outstanding characters of the subfamily Xenodexiinae, the highly modified right pectoral fin and the ctenoid scales, are reflected in the etymology of the generic and specific names: *Xenodexia* comes from ξένος, (strange) and δεξία (right hand); *ctenolepis* from κτείς (comb), λεπίς (scale).

Xenodexia, new genus

Genotype, *Xenodexia ctenolepis*, new species.

In addition to the three features stressed in the subfamily description, various characters separate *Xenodexia* from any of the previously known genera of Poeciliidae. Following the sequence of characters in "An Analysis of the Genera of the Poeciliidae" (Hubbs, 1924: 7–11), the new genus may be further diagnosed as follows: Lower edge of caudal peduncle rounded, with a median series of normal scales. Pelvic fins alike and well developed in both sexes and inserted behind the base of the pectorals. Rays of gonopodium imbricated so as to form an imperfectly closed tube. These characters lead to the Poeciliopsinae, from which *Xenodexia* may well have been derived.

Following the revised analyses of the poeciliopsine genera (Hubbs, 1926: 63–64; 1936: 232–35), these characters may be added: Mouth with lateral cleft much reduced and with the tooth series nearly transverse, slightly hooked backward at sides. Dentary bones soft, but rather tightly conjoined. Teeth strictly uniserial, subvertical, moderately flattened, and in-curved, loosely attached to jaw (but not hairlike). Intestine elongate, coiled on the right side. Gonopodium without hornlike appendages; ray 4 not forming a definite hook at its tip; ray 5 apparently not extending to extreme tip of organ; tube fundamentally on the right side (wholly on the right side in developing male, but at the base and tip only in adult male, in which most of the tube is twisted to the left side by the rolling of the right side of ray 3 over the upper edge of the gonopodium); no obvious antrorse serrae on ray 4. Body slender and scarcely modified for surface swimming (p. 11). Dorsal and anal fins originating on approximately the same vertical (in female). Dorsal fin short (with 9 rays) and moderately rounded. Except for discrepancies in the position of the tube of the gonopodium, in the relative position of the dorsal and anal fins, and in the number of dorsal rays these characters lead toward *Poecilistes*, which, conceivably, might have been ancestral to *Xenodexia*. There are numerous other differences in the detailed structure of the gonopodium (p. 18).

Whether *Xenodexia* is phyletically related to *Poecilistes* or to any other genus of the Poeciliopsinae is problematical, in view of the profound differences noted in the subfamily discussion. It certainly does not line up with the Alfarinae (Howell Rivero and Hubbs, 1936) or the Poeciliinae (Hubbs, 1924: 10–11; 1926: 72–73) and presumably was derived from neither of those specialized groups. If the tubular gonopodia of the Xenodexiinae and the Poeciliopsinae were derived independently, the new group may have stemmed from the Gambusiinae, but if so from what gambusiine genus is not obvious. Origin from the Poeciliopsinae would explain the superfetation practiced by *Xenodexia* (p. 24), for superfetation is particularly characteristic of the poeciliopsines.

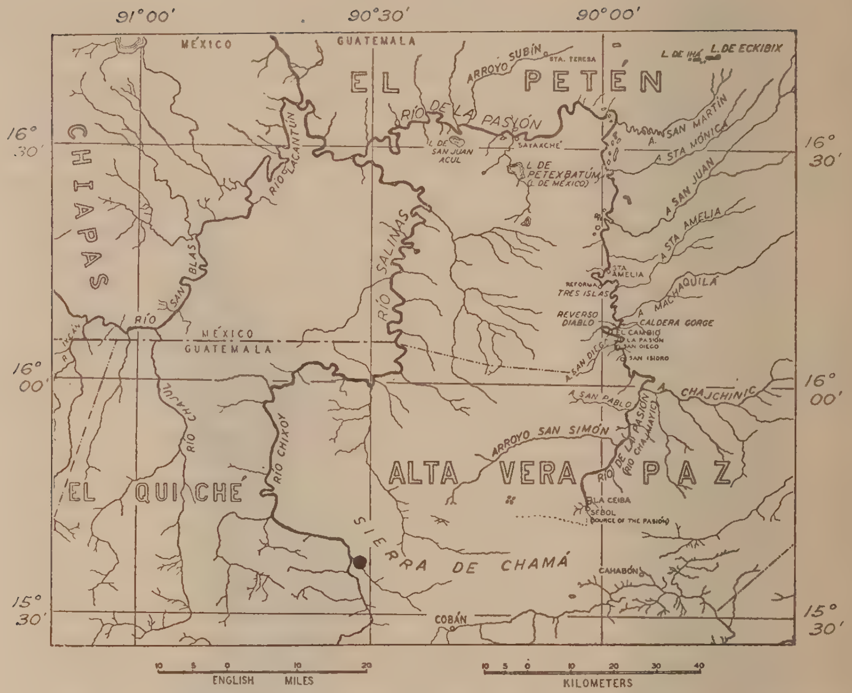
Xenodexia ctenolepis, new species

(Pls. I–IV; Map 1)

TYPE LOCALITY AND HABITAT

This species is known from a single series of 40 specimens seined by L. C. Stuart in Río Seniso (Río Salba), at Finca Chamá, Guatemala, from the hacienda to the mouth of the stream. The locality is about 30 kilometers northwest of Cobán (Map 1). Río Seniso is a small tributary to the deep canyon section of Río Negro (Río Chixoy), which lower down becomes Río Salinas. Río Salinas and Río de la Pasión then unite to form Río Usumacinta, which is perhaps the largest river of Central America.

At the type locality of *Xenodexia ctenolepis*, according to the collector's notes, the Río Seniso is a clear, warm stream about 50 meters wide and as deep as 5 meters (seining was limited to depths less than 1 meter). It flows slowly to swiftly over a gravel bottom between high banks in the rain forest. There is "occasionally a little bottom moss."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MÉXICO
GUATEMALA
EL PETÉN
ARROYO SUBÍN
STA. TERESA
L. DE ECKIBIX
RÍO DE LA PASIÓN
L. DE SAN JUAN ACUL
SAYAXCHÉ
L. DE PETEXBATÚN (L. DE MÉXICO)
A. SAN MARTÍN
A. STA MÓNICA
A. SAN JUAN
A. STA AMELIA
STA AMELIA
REFORMA
TRES ISLAS
A. MACHAQUILÁ
REVERSO DIABLO
CALDERA GORGE
EL CAMBIO
LA PASIÓN
SAN DIEGO
SAN ISIDRO
A. SAN DIEGO
A. SAN PABLO
CHAJCHINIC
CHIAPAS
RÍO LACANTÚN
RÍO SAN BLAS
RÍO SALINAS
RÍO
MÉXICO
GUATEMALA
RÍO CHAJUL
RÍO CHIXOY
EL QUICHÉ
ALTA VERA PAZ
ARROYO SAN SIMÓN
RÍO DE LA PASIÓN
RÍO CHAMANICO
LA CEIBA
SEBOL
SOURCE OF THE PASIÓN
SIERRA DE CHAMÁ
CAHABÓN
COBÁN
10 5 0 10 20
ENGLISH MILES
10 5 0 10 20 30 40
KILOMETERS

MAP 1. Part of Guatemala, showing (black dot) the type locality of *Xenodexia ctenolepis.*

FISH ASSOCIATES AND ZOOGEOGRAPHY

With the types of *Xenodexia ctenolepis,* Stuart collected:

Asytanax fasciatus, intergrades between *A. f. aeneus* (Günther) and the more northern *A. f. mexicanus* (Filippi) (subspecies *aeneus* abounds throughout lower reaches of the Usumacinta system): 24 specimens.

Mollienisia sphenops chisoyensis (Günther, 1866: 342), a dwarf upstream form quite unlike *M. s. macrura* Hubbs (1935: 12–13, Pl. 2, Figs. 2–3) of rivers lower in the Usumacinta system: 165 specimens.

Xiphophorus hellerii guntheri Jordan and Evermann, a rather distinctively colored local form, named by Jordan and Evermann (1896: 702) on the basis of a color sport reported as *Xiphophorus hellerii,* var. γ by Günther (1866: 350; 1869: 485–86, Pl. 87, Figs. 3–4) from a locality close to Río Seniso: 6 specimens. Although the color phase is not worthy of a name, the local form it represents seems to be, for Günther's Figure 2 of a normally colored specimen from the same locality is matched by the specimens from Río Seniso and is unlike specimens from any of the many other localities represented in the Museum of Zoology.

"Thyrina" species (seemingly endemic): 5 specimens.

Cichlasoma species (seemingly endemic): 9 specimens.

From the foregoing list it will be seen that *Xenodexia ctenolepis* inhabits a region with a limited though endemic fish fauna. The contrast is striking with the fauna of the lower parts of the Usumacinta system in El Petén, which I reported in small part early in 1935 and explored later in the same year. It seems unlikely that *Xenodexia* is of wide distribution, for recent collecting in the higher headwaters of the Usumacinta system by Robert R. Miller yielded no additional specimens. Nor did he secure any specimens of the other endemic species of the fauna, of which it is the most notable element.

TYPE SPECIMENS

The 40 type specimens were all collected by L. C. Stuart on May 22, 1931, and were preserved in 10 per cent formalin. Because of transport on muleback the delicate fins are mostly broken, but otherwise the specimens are in good condition. The holotype (U.M.M.Z. No. 105460) is an adult male 40 mm. in standard length. The 39 paratypes (U.M.M.Z. No. 105459) comprise 6 immature males 21 to 23 mm. long, 31 immature females 19 to 32 mm. long, 1 maturing female 39 mm. long, and 1 mature female 41 mm. long.

DESCRIPTION

Counts of fin rays, scales, gill rakers, and head pores are analyzed in Table I. Measurements are recorded in Table II.

Form of Body and Head

In the female the dorsal and ventral contours form almost mirror images of one another. The breeding male has a straighter anterodorsal contour, the muzzle is more downcurved, and the axis is slightly angulated. In these respects the body form of the male slightly approaches that of the surface-swimming cyprinodonts. The male is also somewhat more oblong in shape, due not only to the flattened anterior profile but also to the longer and deeper caudal peduncle. In both sexes the dorsal contour is very obtusely angulated at the front of the dorsal fin. In the male the body is considerably more compressed and flat-sided than in the female: its greatest width is about one-half, rather than about two-thirds, the distance between the origins of the dorsal and anal fins. The greatest depth, near the middle of the trunk, is nearly one-fourth the standard length in the adult female, but only one-fifth that length in the mature male.

In both sexes the head is nearly as wide as deep. The head is considerably shorter, slenderer, and blunter in the adult male than in the adult female. The eye is large and, especially in the male, close to the dorsal contour. When viewed from in front the sides of the head converge downward: the distance between the eyes at the lower border is only two-thirds the interorbital width. The preorbital is narrower than the pupil.

Mouth, Gill, and Intestinal Structures

The mouth is about 0.7 as wide as the interorbital. It is almost strictly transverse as seen from above. Viewed from the side, it is sharply angulated, becoming almost vertical when the mouth is tightly closed. The lateral gape is a little more than one-fourth the transverse width of the mouth. The flat mandibles are almost in contact along the mid-line. Their outer edges converge backward. The maxillaries are separated ventrally by a distance only 0.6 the width of the mouth. The lips are thin; the upper is hardly one-fifth as long as wide.

TABLE I

ANALYSIS OF MERISTIC VARIATION IN TYPE SERIES OF *Xenodexia ctenolepis*

Character	No.	Range	Mean	SD	SE	Holotype
Dorsal rays*	40	8–9	8.97	.16	.02	9
Anal rays*	40	10–11	10.40	.49	.08	10
Caudal rays†	16	16–17	16.06	.25	.06	16?
Pectoral rays (both fins)‡	60	13–15	13.93	.18	.02	14—14
Pelvic rays (both fins)	58	6–6	6.00	.00	.00	6—6
Scales (transverse rows)	40	32–34	32.87	.56	.09	33
Gill rakers on first arch	4	15–17	15.75	......	......	......
Preopercular pores at stated size groups:§						
19 to 25 mm.	44	6–7	6.25	.43	.07	......
26 to 32 mm.	28	7–7	7.00	.00	.00	......
34 to 41 mm.	8	7–7	7.00	.00	.00	7—7
Preorbital pores at stated size groups:§						
19 to 25 mm.	44	0–3	0.30	.84	.13	......
26 to 32 mm.	28	3–3	3.00	.00	.00	......
34 to 41 mm.	8	3–4	3.87	.36	.13	4—4

* Total number of rays, counting the last 2 elements as one ray.

† Principal rays (branched rays plus 2). Owing to injury of the fin, half of the counts are questionable.

‡ Both fins were counted. The count includes a short ray at the upper edge of the fin and all discernible rudiments at the lower end.

§ Standard lengths. The pores were counted on both sides. Neuromast pits or grooves without pores were not counted.

The amber teeth form a single series, with only slight irregularities in the file. Across the mid-line in each jaw the series is slightly bent backward, but is nearly continuous. Each series is slightly hooked around the corner of the mouth, but is scarcely extended onto the lateral gape. The teeth are subvertical, moderately strong and firm, somewhat flattened medially, not very sharply pointed, moderately curved backward.

The gill membranes are narrowly connected by a free fold located on a vertical approximately below the posterior edge of the preopercle. The upper limb of the first gill arch is attached to the roof of the mouth. The rather sharp gill rakers extend slightly onto the skin surface over the base of the upper arch.

The intestine has a smaller caliber than in *Poecilistes* and is longer and more extensively coiled (Pl. IV). There are about 5 coils. The outside diameter of the largest coil is one-third the standard length, instead of one-fourth as in *Poecilistes*. Posteriorly this coil extends to a vertical that intersects the ventral contour at a point twice as far from the pelvic insertion as from the anal origin, rather than as in *Poecilistes*, at a point little behind the pelvic base. As is usual, the coils of the intestine lie against the right body wall.

TABLE II

Measurements of *Xenodexia ctenolepis* Expressed in Thousandths of Standard Length

	Adult Male (Holotype)	Mature Female	Maturing Female	Immature Females (7)	
				Range	Mean
Standard length, mm.	40.1	40.5	39.1	28–34	30.6
Body depth	227	228	221	193–219	209
Caudal peduncle depth	145	132	130	125–131	127
Predorsal length	553	581	582	572–592	583
Prepelvic length	434	452	442	439–455	446
Anal origin to caudal base	512	420	437	421–439	429
Head length	220	238	243	249–263	255
Head width	135	146	140	147–158	150
Head depth	141	157	156	159–167	164
Snout length	54	75	75	72–77	75
Orbit length	81	82	84	83–91	86
Postorbital length	88	95	97	101–108	104
Fleshy interorbital width	85	110	114	102–118	113
Mouth width	61	76	75	74–79	77
Fin lengths:					
Dorsal base	117	106	107	99–110	105
Depressed dorsal	Injured	207	211	183–220	207
Depressed anal	438	175	187	174–192	182
Caudal (middle rays)	Injured	Injured	224	207–241	227*
Pectoral	219	185	Injured	Injured	....
Pelvic	Injured	142	135	131–149	139†

* Based on 3 measurements.
† Based on 6 measurements.

Axial Skeleton

Except for special modifications attributable to the great extension of the coelom into the urosome, in both sexes, and to the elaboration of the gonopodial suspensorium, in the adult male, the axial skeleton, as seen in the X-ray photographs (Pl. IV) and in partial dissections of the maturing female, is of the typical poeciliid type. Including the hypural the vertebrae number 34. The axis bears no ribs and apparently no neural spine. It is tightly secured to the skull by a suture that is oblique and angulated laterally. Each of the other vertebrae bears a neural spine and, in each sex, the last 16 vertebrae in advance of the hypural appear from the X-ray photographs to bear similar, scarcely modified hemal spines. On partial dissection, however, the first 3 of these structures in the female are seen to be spread apart at the base, the first almost completely, the third slightly, to surround the tip of the air bladder. In the X-ray photographs of the adult male (reproduced as Pl. IV, Figs. 1–2), the first of these 3 ventral processes is seen to be highly modified and the next 2 show some basal modification (p. 21). Therefore, there are not more than 14 fully typical caudal vertebrae in advance of the hypural.

The first 11 ribs of each side (in the female overlying the gut) are strong. The first rib, borne by the second vertebra, is the least oblique. On the thirteenth to the sixteenth vertebrae there follow 4 more pairs of ribs, decreasing in length and thickness. One or 2 additional, rudimentary pairs may exist.

Vertebrae 13 to 19, therefore, show transition from the precaudal to the caudal type, with the thirteenth little modified. In the female, vertebrae 14 to 18, which carry strong gonapophyses in the adult male (p. 21), do not bear normal hemal spines, but grade from a nearly typical precaudal vertebra, with scarcely developed parapophyses, to one in which parapophyses barely unite.

Individual vertebrae are of slender hourglass shape, decreasing in length but not in sutural height toward the hypural. The hypural is of the typical homocercal type. There appears to be some heavy calcification a short distance behind its front suture. Four vertebrae in addition to the hypural support the caudal fin.

Scales

As already indicated, the scales of *Xenodexia ctenolepis* are unique among cyprinodonts in being ctenoid (Pl. III). The spines near the scale margin are not to be confused with the cilia-like nuptial organs of the breeding male of some oviparous cyprinodonts (Newman, 1909). They are present in females as well as males and in young as well as adults. They are hard, needle-sharp, denticle-like structures, quite like the ctenii of acanthopterygian fishes. They form near the straightish scale margin and remain essentially uniserial, though the upper and lower ones are seen on close examination to belong to a row behind the series that occupies the middle half of the denticulate border. Presumably the penultimate row increases in height at the dorsal and ventral ends, but, before the process is completed, is followed medially by a new row. The ctenii of the next to last row are represented only by the bases in the median part of the row, opposite the developed part of the last row. Still farther forward even the bases disappear, as they become completely overgrown by the outer layers of the scale. This process of overgrowth appears to begin almost as soon as the ctenii are first formed. After the ctenii begin to develop, when the scale is about one-fourth the adult size, the posterior field grows very little. In the adult the ctenii-bearing, posterior field is only about one-fourteenth as long as high, and the entire posterior field from the center of the focus is only about one-sixth as long as the height of the denticulate part of the scale border. The length of the anterior field of the scale, in contrast, is about one-half the height of the entire scale. The whole scale is about two-thirds as long as high. Circuli near the focus and on the lateral fields are rather coarse. In the region of the ctenii there are no circuli. Between the ctenii and a slight groove bounding the lateral fields proper there is a narrow band on which there are traces only of circuli. On the anterior field the circuli are about twice as crowded as on the lateral fields. The weakly angulated anterior border is about one-fourth higher than the posterior border. The moderately divergent radii number about 12 in the half-grown and about 15 in the adult. Between the radii most of the segments of the circuli are curved backward.

The ctenoid scales cover most of the body, but the ctenii are lacking on the scales of the head and the immediately adjacent parts of the body. The spinules are either weak or absent on the scales of the breast and pectoral fin base and often on a few body scales near the caudal base.

The arrangement of the scales on the body is quite typical of the cyprinodonts. The axial scale row is slightly bent upward anteriorly, to overlie throughout the axial septum of the body-wall muscles. This row is separated by 3 parallel rows from the middorsal row, which is split by the dorsal fin, and by 3 rows from the median ventral series of the caudal peduncle (close to the head only 2 rows may intervene between the axial and middorsal rows; on the abdomen the highly regular arrangement breaks down). This pattern of lepidosis was found, by an examination of the nearly complete range of species in the Museum of Zoology, to characterize all Poeciliidae with one minor exception: in the deep-bodied forms of *Mollienisia,* as *M. velifera* Regan and *M. sphenops altissima* Hubbs, 4 rows intervene between the axial series and the row on the ventral edge of the peduncle. The same pattern characterizes many of the oviparous cyprinodonts as well.

There is some modification of the scales near the bases of the fins, including the pelvic (p. 18). The scales at the anal base are slightly modified, especially at the gonopodial base on the right side (p. 21). There is a large thick scale on the upper anterior part of the broad pectoral base. It is separated from the scaleless fin base by a row of moderately large scales and then by several small thin scales, which on the right or clasper side of the mature male become thickened to form a definite hard rim. This rim closely overlies a rather deep pocket and is continued along a rounded lobe well below and behind the lower end of the pectoral base. The arrangement of scales on the right pectoral base is shown in Plate II, Figure 3.

Fundamentally, the lepidosis of the head is also typically cyprinodont, but some of the details are probably distinctive. The scales on the top of the head are large. The nonimbricate scale is one of a pair that nearly covers the posterior half of the interorbital space. This pair of scales is bounded behind by a large median scale and 2 smaller lateral ones. The median scale makes contact with the first dorsal body scale and thus excludes a pair of large scales from the mid-line. In front of the 2 interorbital scales mentioned above there is a large shield-shaped scale. In front of this scale are 2 medium-sized scales and in front of these, 2 near the mid-line and 1, occasionally 2, at the side. There are 3 small scales on each side of the interorbital. Three large scales carry the axial row of the body forward to behind the upper posterior corner of the eye, and about 3 scales separate them from the enlarged scales on top of head. The axial row is separated by a row of 3 or 4 thin scales from the opercular scales. On the opercles there is a subvertical row of 3 very large scales, followed by a submarginal row of 2 to 4 usually smaller scales and preceded, behind the rounded preopercular angle, by a row of 2 to 4 small scales. On the cheek there are 4 to 6 small thin scales along the lower and lower-posterior margin of the orbit and 2 to 4 extra scales between this row and the preopercular angle. The muzzle and the lower anterior side of the head are scaleless.

Lateral-line Structures

As in other Poeciliidae typical lateral-line pores are not developed, but are represented by neuromast or pit organs (Pl. III), 1 to each scale, aligned in a pattern distinctive of the family (p. 8). Anteriorly, the organs disappear in the axial series but are developed instead on several scales of the next higher row. There are very few of these pits on the dorsal part of the body. The series along the second scale row above the midventral line of the caudal peduncle is incomplete. The pits occur also on the larger scales above the bases of the anal and pelvic fins and on many of the scales of the breast.

On the head the arrangement of the organs is of the cyprinodont type (Gosline, 1949). There is nothing in its canal and pore pattern to set *Xenodexia* sharply apart from many other genera, particularly in the Poeciliidae. In the adult, above and behind the eye, there is a short segment of lateral line with a pore at either end. Just mesad to this there is a rather indefinite structure. There is a short canal on each side of the interorbital along either side of the large median scale. Closer to the mouth there is a well-separated pair of short grooves, each of which in the adult becomes covered to form a tube with a pore at each end. The preorbital canal is gently curved, paralleling the orbit. It is open and without pores in the young, but, as indicated in Table I, gradually becomes covered with membrane, leaving 3 pores in the half-grown and usually 4 in the adult. When there are only 3 pores, there is usually a neuromast organ below, that may or may not lie in the same fossa as the lowest pore. Occasionally, when 4 pores are developed in the adult, there is still a neuromast organ below. When there are only 2 openings the median pore (to be) is connected with the one either below or above. The infraorbital canal has no pores, but is represented by a row of very small, close-set sense organs. The preopercular canal is a closed tube with 7 pores in the adult, 3 above and 3 in front of the angle. In the smaller specimens examined, the 2 upper pores are united so as to give a count of 6 (Table I). Anteriorly in the same series there is on each side a rather indefinite sense organ just inside the maxillary and a somewhat similar structure, also without a definite pore, on the chin. On each side of the opercles there are 4 small, low, slightly recessed sensory papillae, arranged as shown on Plate I.

Coloration

The coloration is rather plain and is essentially alike in male and female. The young are much like the adults, except that the lateral band is narrower and less intense. The advanced embryos (p. 24) differ from the 20-mm. young in several respects, particularly in the double file of melanophores along the lower edge of the caudal peduncle and along the middorsal line. The development of pigmentation is briefly traced on page 24.

The most prominent color markings are the dark lateral band and the dark margining of the scale pockets. The lateral band, extending from an indefinite origin near the middle of the trunk to but not onto the base of the caudal fin, is an intense suffusion about the fine black axial streak. The dark scale-pocket borders are broad and intense near the back, are narrow but remain conspicuous on the mid-sides, become faint near the lower edge of the urosome, and disappear on the belly and breast. The scale pockets in the temporal region retain the dark border and the light centers, but the parietal–occipital region is dark. The top of the muzzle is somewhat variegated. There is a rather indistinct dark streak on the head behind the eye, but below this mark and below the blackish transverse parts of the lips the head is pale. Except for a fine black streak on each edge of the dorsal, anal, caudal, and pectoral rays, the fins are whitish. Most of the processes of the pectoral clasper are puncticulate. There are also some fine specks on the gonopodium, on the rolled-over part of ray 3.

My recollection is that the lower sides of the specimens, when fresh, were more or less yellowish, definitely yellow in the adult male.

Fin Structure

The basic fin structure is typical of the cyprinodonts. The dorsal fin includes 2 unbranched rays. The first is about half as long as the second, which extends nearly to the tip of the fin. The 7, occasionally 6, other rays are branched. The anal fin of the young and the female comprises 3 unbranched rays (the first very short, the second moderately short, and the third extending nearly to the tip of the fin) and 7 or 8 branched rays. There are 15, occasionally 16 branched caudal rays (16 or 17 principal), and, in addition, above and below, 1 or 2 rather well-developed marginal rays and several small procurrent ones. The pectoral comprises 1 short and 1 long simple ray and 11 to 13 branched rays. The pelvic has 1 unbranched and 5 branched rays. All rays except the very shortest procurrent caudal rays are articulated.

The dorsal fin varies from rounded to rather sharply pointed. The caudal fin is truncate. The pectoral is moderately rounded; the pelvic, pointed. In the adult female the pectoral reaches almost to the vertical from the pelvic insertion; the pelvic, to the anus or to the genital opening. The pelvic fins are essentially alike in the two sexes, as are also the pectoral fins proper, despite the profound modification in the adult male of the pectoral fin base on the right side. The pelvics are widely separated by a basal interspace about thrice as wide as either fin base. Between the base of the fins there are 3 scales, of which the outer one on each side overlaps the fin base, but there is no special sheath of scales, such as is developed in many but not all cyprinodonts. In the young and in the female the dorsal and anal origins are on approximately the same vertical. The relations of the fins in the adult male are shown on Plate I. The fin-ray counts are indicated in Table I and fin measurements in Table II.

Gonopodium

In confirmation of the general rule that genitalial characters are of outstanding value as indices of both relationship and differentiation, I find that the gonopodium of *Xenodexia* (Pl. I) is definitely of the poeciliid type (p. 7) and that it has very many highly distinctive features.

The organ is rolled tightly into a narrow and very long, imperfectly enclosed tube. The tube is basically on the right side, but is twisted onto the upper left side by the rolling over of the cover, which is formed by the broad spinous segments of ray 3. In 1 of the series of immature males 21 to 23 mm. long, the anal fin shows a slight cupping on the right side.

The gonopodium is nearly 0.45 as long as the head and body. It is carried close to the ventral edge of the elongate caudal peduncle and almost reaches the lower procurrent caudal rays. It is perhaps longer proportionately than in any other poeciliid.

The very short rays 1 and 2 lie in a translucent crest along the greatly swollen base of ray 3. Segmentation has become obliterated in the basal two-fifths of rays 1 and 2 and in a basal section of ray 3 that is longer than broad. As seen from the right side, as in the enlarged figure (Pl. I, Fig. 2), the swollen base is arched downward.

At about the end of the first fourth of the length of the gonopodium, ray 3 starts the prominent upward and leftward roll that deflects the tube onto the opposite (left) side. This rolled section, which extends to within one-seventh of the length of the gonopodium from the tip, is constructed from the right side of 52 segments, of which all but the last one are much widened and are definitely spinous at the edge of the roll.

Where the main roll starts, near the base of the gonopodium, a shallow groove arises along the left side of ray 3. Along the basal part of the roll this groove becomes narrow and is twisted to the ventral edge of the intromittent organ. The right edge of the groove then becomes elevated until it forms a ridge, which, opposite the last 21 segments of the main or right-side roll, becomes rolled in the opposite direction (counterclockwise) under the ventral edge of the gonopodium to the left side. Thus, in this section, the broadly expanded and transversely curved ray 3 has 2 edges, both directed toward the left, 1 above and 1 below. The shorter, more ventral roll partly encloses a secondary tube. The rolls end near the same point, the shorter one the less abruptly. In the ventral roll there are about 20 spinous elements similar to those of the main or dorsal roll, although widely separated. The ventral roll covers the overlap of ray 3 on ray 4. The 20 spines of the lower roll are parts of the same segments that form the 20 distalmost spines of the dorsal roll. On external scrutiny it is not clear how the paired halves of ray 3 are involved in the excessive specialization of the segments in the doubly rolled section. At first consideration it would be thought that the halves merely diverge to roll in opposite directions, but to remain in contact at the front edge. At the origin of the main roll, however, it appears that the whole ray, with the halves closely joined, is involved in the formation of the roll.

Beyond the doubly rolled section, ray 3 extends to the extreme tip of the gonopodium. Here the ray is much narrower and at first is much less modified. On its outer half the terminal part bears 2 small flaps, prominent only on high magnification. The flap on the right side rises abruptly, with an obliquely truncate base and a subbasal point, but grades outward into the edge of the ray. On the opposite side of the gonopodial tip is a longer, wider, and thicker dermal process that extends almost straight outward toward the left. It rises rather abruptly opposite the second segment of ray 3 basad to the origin of the right-side flap and descends gradually to the edge of the gonopodium very close to the extreme tip.

Rays 4 and 5 are presumably branched, as in the female and young and as in the gonopodia of other poeciliids, though, except in one short section of ray 4, the complex folding and the tube structure render the identification of the branches dubious in the single mature male at hand.

From the right side ray 4 is scarcely visible at the extreme base and extreme tip of the organ and throughout most of the length is completely hidden. As seen from the left side this ray is slender opposite the thickest, basal part of ray 3. It then arches upward and broadens. As it does so the segments become strongly directed distad, so that each joint is conspicuously oblique. In this respect rays 4 and 3 contrast, for the segments of 3 are nearly transverse throughout. In this section the segments of ray 4 correspond closely in width with those of ray 3. Many abutting segments coincide, but the independence of the rays is shown by the fact that in places 2 segments of one ray lie opposite a single segment of the other ray. The segments are short and broad near the base of ray 4 but become longer and narrower outward: just proximal to the origin of the main rolled part of ray 3 the oblique segments are about one-fourth as long as wide; about two-fifths of the way out on the gonopodium the rhomboidal segments are about as long as broad. Near the middle of the length of the gonopodium ray 4 becomes hardly visible as it runs in an oblique fleshy ridge. Toward the extreme tip the ray is deflected from the left side to the bottom of the gonopodium but it extends to the extreme tip. Near the last downward bend, very close to the extreme tip, the segments of ray 4 become conspicuous again and are much broader than long; they are also much broader than the opposite segments of ray 3. Near the end of the dorsal roll of ray 3 the posterior branch of ray 4 is visible to the left and slightly below the anterior branch. Its segments are longer than wide whereas those of ray 4*a* in this region are wider than long. As far as I can see there is no conspicuous fusion, spination, or bilateral asymmetry of the segments of either branch of ray 4.

Ray 5 is rather slender near the base. It is even more strongly arched than ray 4 and becomes somewhat strengthened opposite the broadest and most oblique segments of that ray. Along much of the length of the gonopodium ray 5 is not readily visible. Toward the tip on the right side it seems to form the upper lip of the tube out to the extreme tip of the gonopodium.

Rays 6 and 7 are moderately curved, and considerably thickened, with subquadrate segments, where they form the roof of the basal part of the tube. A fleshy process from the posterior edge of ray 3 nearly closes the extreme base of the tube. The membranes about rays 6 and 7 are also much thickened and ray 6 extends into a pointed lobe. Along the front edge of the basal part of ray 6 the segments flare apart. The following rays are much slenderer and the last ones are so short and delicate as to be countable only with extreme care.

Specialized scales, somewhat thicker and stronger than usual, form a sheath, with a definite edge, over the extreme base of the gonopodium, on the right side only. The anterior base of the gonopodium is embraced by a parabolic membrane, much as the anal fin in the female of *Fundulus* is surrounded by the oviducal pouch.

Gonopodial Suspensorium

As noted earlier (p. 7), and as seen in X-ray photographs, two of which are reproduced (Pl. IV, Figs. 1–2), the gonopodial suspensorium of *Xenodexia ctenolepis* is of the poeciliid type. The suspensorium is connected with the vertebrae that are transitional between the precaudal and caudal types (p. 14). Vertebra 13 is definitely precaudal and scarcely modified.

The 4 strong gonapophyses (specialized hemal spines supporting the interhemals) are attached to vertebrae 14 to 17. They are about one-third as long as the body is deep. All are flattened toward the tip and all are angled forward. The basal halves form angles with the vertebral column of about 86, 79, 95, and 110 degrees. The angles formed by the axes of the 2 limbs of each gonapophysis are about 62, 75, 85, and 76 degrees. The especially broad distal part of the second one is a sharp triangle of about 22 degrees. The most ventral parts of the gonapophyses are on a line that slopes downward at an angle of 23 degrees with the posterior vertebrae of the caudal peduncle. There are, apparently, no definite uncinatoid processes. Parapophyses seem to be scarcely developed on vertebra 14 (the first with a gonapophysis), for the ribs appear to be sessile, but on the 6 following vertebrae, parapophyses are apparently developed. They seem to be moderately strong though short on vertebrae 17 (the last with a gonapophysis) and 18, but weaker on the vertebrae on either side. Ribs are developed at least as far as the sixteenth vertebra; possibly, to a weak degree, on 1 or 2 more.

The first gonapophysis seems to contact the upper posterior corner of the compound interhemal. The second and third support the posterior interhemals. The fourth probably has only a ligamentary connection with the interspinous bones. The anterior tip of the third apparently contacts the lower posterior angle of the second.

The compound interhemal is obviously a strong, rather well consolidated rod or plate. Its dimensions, determined from an X-ray photograph (Pl. IV, Fig. 1) and expressed as thousandths of the the standard length, are: greatest length, 112; greatest anteroposterior width, near top, 50; least anteroposterior width, 22; greatest width near ventral edge, 39; least distance from vertebral column, 47. The constituent interhemals are not certainly identifiable. The first is probably very short, since it is so in other poeciliids. The clearer X-ray photograph shows at least 3 rods, of which the median is slender and the others broad and rounded at the upper edge. Following the compound structure is a slender interhemal that dorsally seems to touch the main structure, as well as the tips of the first 2 gonapophyses, but ventrally diverges slightly from the compound interhemal, as well as from the next of the several following, obliquely set, narrow interhemals.

Pectoral Clasper

As previously noted (p. 5), though the left pectoral is essentially unmodified, the right fin and surrounding structures are marvelously specialized (Pl. II, Figs. 2–3). Behind this fin is a voluminous pocket, in the 40 mm. fish fully 5 mm. high, 2 mm. across when the fin base is extended outward, and 3 mm. deep, not including the fin itself. The muscle mass on the breast at the base of the right pectoral seems to be twice as thick and twice as expansive in area as the corresponding muscle mass on the left side. Along the base of the right fin is a hard sheath made of very thick scales (pp. 15–16). This sheath forms a pocket at the base of the fin and is extended as a rounded lobe for a full millimeter (more than 2 per cent of the standard length of the fish) below and beyond the lower end of the fin.

The fin rays, however, are only slightly specialized. The uppermost ray is a little enlarged and instead of forming a splint at the base of the next ray is well separated from it. This second ray is a little more arched than usual and is considerably thickened. Instead of being branched, as it is in the adult female, the third ray remains simple.

The clasper-like structures are outgrowths from the upper part of the fin base. How much modified the skeleton of the pectoral girdle may be is not fully clear from the X-ray pictures, and dissection of the holotype (the only known adult male) seems unwise.

The clasper proper comprises an assortment of hooks, pads, and other processes (Pl. II, Figs. 2–3). One of the most conspicuous is a long, complexly curved structure labeled *a*. Its main axis is supported by a bone-hard, translucent rod, which arises, opposite the upper base of the fin, from the upper part of a large soft pad (*b*). The rod extends backward and slightly upward, then curves abruptly upward and finally mesad. Near its first bend it supports a fleshy keel (*c*). On the posterior edge of its tip it gives off 2 small processes partly enclosing a semicircular recess. On the inside, opposite the uppermost ray, process *a* is connected with the outer face of the fin by a thin membrane (*d*). From the point where the edge of the membrane is attached to process *a*, there extends downward a fleshy, flask-shaped structure, first as a pointed tip in the membrane and then as a bulbous expansion (*e*) on the base of the fin. Five processes (*f–j*) of varied size, shape, and hardness arise from the upper edge of the fin near its base. On the upper part of the shoulder girdle is a much larger bilobed fleshy structure (*k*). The lower lobe is closely bound to the base of process *a* and the upper lobe is loosely connected by a membrane with lobe *f*.

It seems obvious that this complex organ is a clasper. Exactly how it functions can only be surmised. The large deep pocket behind the structure and the known clasping habits of other fishes lead one at first to suspect that the male approaches the female from the one side and clasps her with the modified pectoral. A surprising yet more plausible theory as to the function of the clasper has been suggested by Reeve M. Bailey. He has pointed out that if the gonopodium is deflected forward it will be caught and held in position by process *a* so as to leave the functional tip just exposed over the outer part of the large pocket. When an adult female is inserted into the pocket so that the modified pectoral fin of the male clamps down on the anal fin of the female, it is seen that the tip of the gonopodium comes into contact with the genital opening of the female, which seems to be modified so as to receive the gonopodial tip when the two fish are in this position.

Sex Organs of Female

The genital papilla of the one fully mature female at hand is very interestingly modified (Pl. II, Fig. 1). As seen from the left side the papilla is a subconical structure about 1 mm. long (2.5 per cent of the standard length). It has a bifurcate tip, of which the anterior process is the longer and the slenderer. From the right side it may be seen that these two tips are the ends of the fleshy rims of a largely open tube, which curves outward toward the right near the middle of the papilla and then inward into the oviduct between the expanded and approximated bases of the two rims.

The mode of formation of this complex genital opening is indicated by the maturing female, in which the two tips arise almost side by side from the fleshy region between the anus and the anal fin. Already the tip of the right side is somewhat the more anterior. Behind the two tips a groove extends backward and toward the left. The groove, however, faces both backward and toward the right. A slight twisting of the papilla as it develops obviously suffices to shift the groove into the lateral position seen in the adult female.

The ovary, which has a definite oviduct, is slightly diverted to the left side. The embryos are separated, each in its own pocket, by thin transparent membranes. In the young female the gonad is slender, but contrasts with the immature testis in having smooth walls rather than a crenate border, in being cylindrical instead of flattened, in being more translucent, in having a definite stalk (the oviduct), and in not showing a line of fusion of the left and right organs. Furthermore, under high magnification, the ova can be distinguished from the tubules of the testis.

SUPERFETATION AND DEVELOPMENT OF PIGMENTATION

Since the mature female contains embryos in various stages of development, *Xenodexia* is added to the list of poeciliids in which development involves superfetation (Turner, 1937, 1940; Scrimshaw, 1944). In its ovary, 5 × 9 mm. in major dimensions, with major irregularities due to the protuberances about embryos, there is one maturing or mature egg 1.31 × 1.64 mm. in major diameters and 6 embryos in 5 stages of development: (1) The smallest embryo, about 3.0 mm. long, retains a yolk sac more than 0.5 mm. in diameter. It is unpigmented except in the eyes. (2) Two embryos, each about 6.0 mm. long, have considerable pigment on the top of the head, 2 rows of melanophores along the middorsal line, 1 row along the axial septum, and 2 rows along the lower edge of the caudal peduncle and the base of the anal fin. (3) One embryo, 8.3 mm. long, is considerably more advanced in development and has the head and the middle of the trunk well pigmented. (4) One embryo, 9.7 mm. long, shows further advances in development, but is obviously not yet ready for birth. Melanophore pigment is developing along the edges of the scale pockets near the back. (5) One embryo, 10.5 mm. long, seems to be about ready for birth. The pigmentation is now well developed around the scale pockets and the fish looks much like the juveniles about 20 mm. long. The advanced embryos, however, differ in several respects from the young at that size (p. 17).

Superfetation is especially characteristic of the subfamily Poeciliopsinae, which the genus *Xenodexia* resembles in gonopodial structure and some other respects (p. 9).

SEX RATIO

The 40 known specimens comprise 33 females and only 7 males. To insure accuracy in sex identification all specimens except the adult male were opened to inspect the gonad. For the maturing and mature fish the ratio was 2 females to 1 male. Of much greater significance in estimating the sex ratio is the observation that the immature fish comprised 31 females and only 6 males. Since most of these fish showed almost no enlargement of the gonad, differential schooling is highly improbable and differential mortality seems unlikely. The disparity in the ratio 31 to 6 is trustworthy, for the χ^2 value is 16.9 and the probability value 3.7×10^{-5}. It is probable, therefore, that females of *Xenodexia* markedly outnumber the males, even in the young fish. The disturbed sex ratio may be correlated with the perfection of the inseminating mechanism.

SEXUAL DIMORPHISM IN SIZE AND FORM

Despite the aberrant sex ratio and the strong sexual dimorphism in other respects, the sexes of *Xenodexia,* unlike those of the Poeciliopsinae and many other poeciliids, are probably similar in size. The 1 adult male now measures 40.1 mm. in standard length; the maturing female, 39.1 mm. and the mature female, 40.5 mm. The 6 juvenile males are 21 to 23 mm. long; 24 of the 31 immature females are 19 to 25 mm. long. The 7 larger immature females measure 28 to 34 mm.

In form and structure the sexual dimorphism is very notable. The secondary sexual modification of the anal fin and associated structures is rather extreme (Pls. I, IV; pp. 18–22). There are considerable differences in the general form of the body and head (pp. 11–12). The comparative measurements (Table II) indicate that the adult male differs from the female and young in many ways: The body is deeper than in any except pregnant females. The caudal peduncle is markedly deeper. The dorsal and pelvic fins are considerably advanced in position; the anal fin, very markedly so. The head is shorter, narrower, and slenderer, in proportion to the standard length, though not in relation to the head length. The snout is much shorter, only about one-fourth rather than one-third the head length, and 54 rather than 72 to 77 thousandths of the standard length. The eye is a little larger relative to the head length. The interorbital and the mouth are narrower, in reference to head length as well as body size. The dorsal base is longer and the pectoral fin may be longer. The sexual dimorphism is of the poeciliid type.

ACKNOWLEDGMENTS

In the preparation of this paper I have received much help from several colleagues, mostly staff members of the University of Michigan. First, I wish to thank Laurence C. Stuart for the time and effort he spent in collecting fishes in many out-of-the-way parts of Guatemala. My successor in the Museum of Zoology, Reeve M. Bailey, has given every possible co-operation in my studies, both in Ann Arbor and in La Jolla, and has made a very helpful suggestion as to the function of the pectoral clasper. Laura C. Hubbs assisted in statistical calculations and in other ways. William A. Gosline kindly took the needed X-ray photographs. William Cristanelli of the Institute for Fisheries Research, Michigan Department of Conservation, took the photograph of the ctenoid scale. It is a particular pleasure to acknowledge with appreciation Grace Eager's initial work on the drawings, which were left unfinished by her untimely death. Alma W. Froderstrom has completed them.

SUMMARY

Xenodexia ctenolepis, a new genus and species from an area of endemism in the upper part of the Río Usumacinta system in Guatemala, is so highly specialized as to call for its segregation in a distinct subfamily, Xenodexiinae. Its most distinctive features are an elaborate unilateral pectoral-fin clasper of the adult male—a structure unique among fishes; ctenoid scales, hitherto unknown and unpredicted in the order Cyprinodontes; and an extreme extension of the body cavity into the urosome. A large variety of characters, including genital and genitalial structures of high taxonomic value and 2 recently discovered features that are independent of sex, indicate that this bizarre fish should be classed in the family Poeciliidae, but alternative possibilities are not wholly eliminated. *Xenodexia* may have been derived from the Poeciliopsinae, but the very complex tubular form of the gonopodium may have been evolved independently. In *Xenodexia* this structure (the intromittent organ) is extremely long and very complex.

It seems probable that the ctenii on the scales of *Xenodexia* represent reversible evolution, but probably only in the sense that the ctenii were long lost in phenotypic expression, not in genetic potential. The discovery of ctenoid scales in a member of the order adds weight to the view that the Cyprinodontes were derived from an ancestor, possibly an acanthopterygian, well advanced along the teleost line of evolution.

Insemination in *Xenodexia* is presumably effected when the male holds the female in the recess behind the highly modified base of his right pectoral fin, the upper part of which is replete with hard and fleshy hooks and pads. The forward-turned gonopodium is probably held securely in place by the main hook of the clasper. In this position its fleshy tubular tip would fit into the clasped female's genital papilla, which is grooved on the right side, to complete what seems to be a lock-and-key mechanism. Perhaps in correlation with the perfection of the inseminating mechanism, the males seem to be greatly outnumbered by the females. The sexes appear to attain about the same size, but sexual dimorphism in form and structure is rather extreme. *Xenodexia ctenolepis* is one of the poeciliids, the development of which involves superfetation. As many as 5 broods in different stages of development are present at one time in the ovary.

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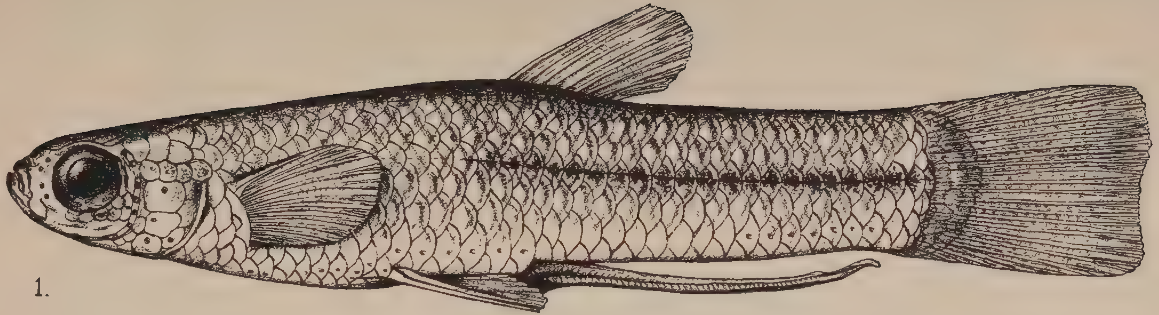
PLATE I

FIG. 1. *Xenodexia ctenolepis,* holotype, mature male, from left side. The dorsal, pectoral, and pelvic fins, damaged in the holotype, were reconstructed from female paratypes.

FIG. 2. Gonopodium of holotype of *Xenodexia ctenolepis,* from right side.

Drawings begun by Grace Eager, completed by Alma W. Froderstrom.

PLATE I



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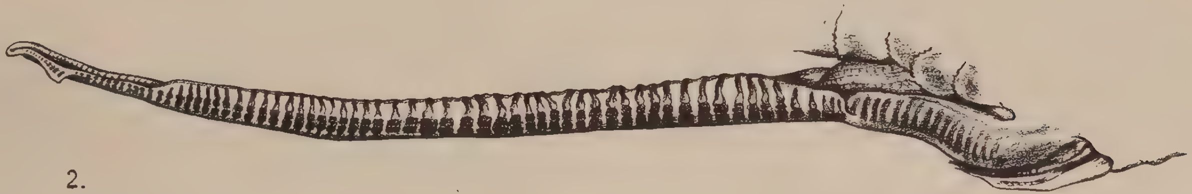

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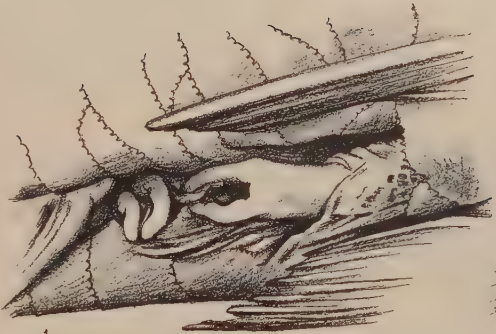
PLATE II



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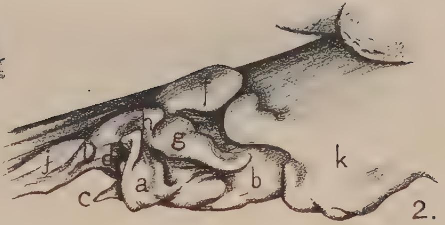
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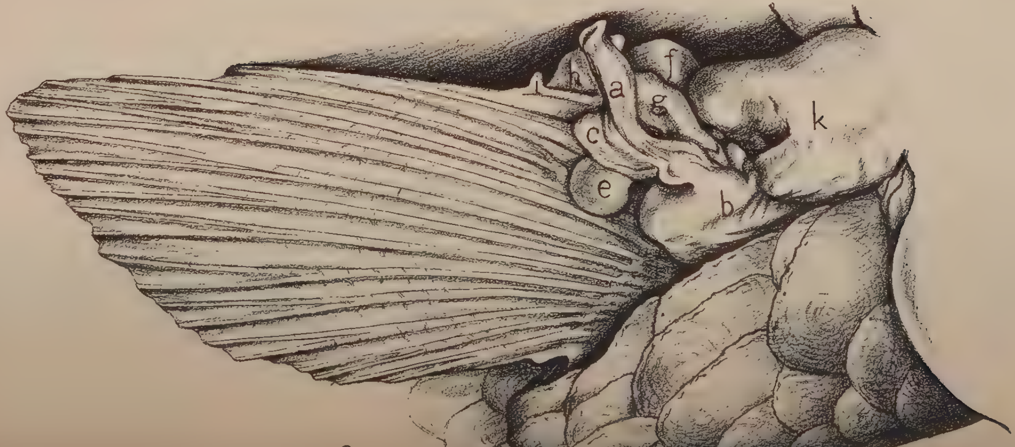


3.

PLATE II

Copulatory structures of *Xenodexia ctenolepis.*

FIG. 1. Genital papilla of mature female paratype (41 mm. long), from right side.

FIG. 2. Dorsal view of pectoral clasper of holotype. For explanation see text (pp. 22–23).

FIG. 3. Lateral view of the same structure. The left pectoral fin is unmodified.

Drawings begun by Grace Eager, completed by Alma W. Froderstrom.

PLATE III

Scale from the axial series of adult female (41 mm. long) of *Xenodexia ctenolepis*, showing the ctenii and a neuromast or pit organ.

PLATE III

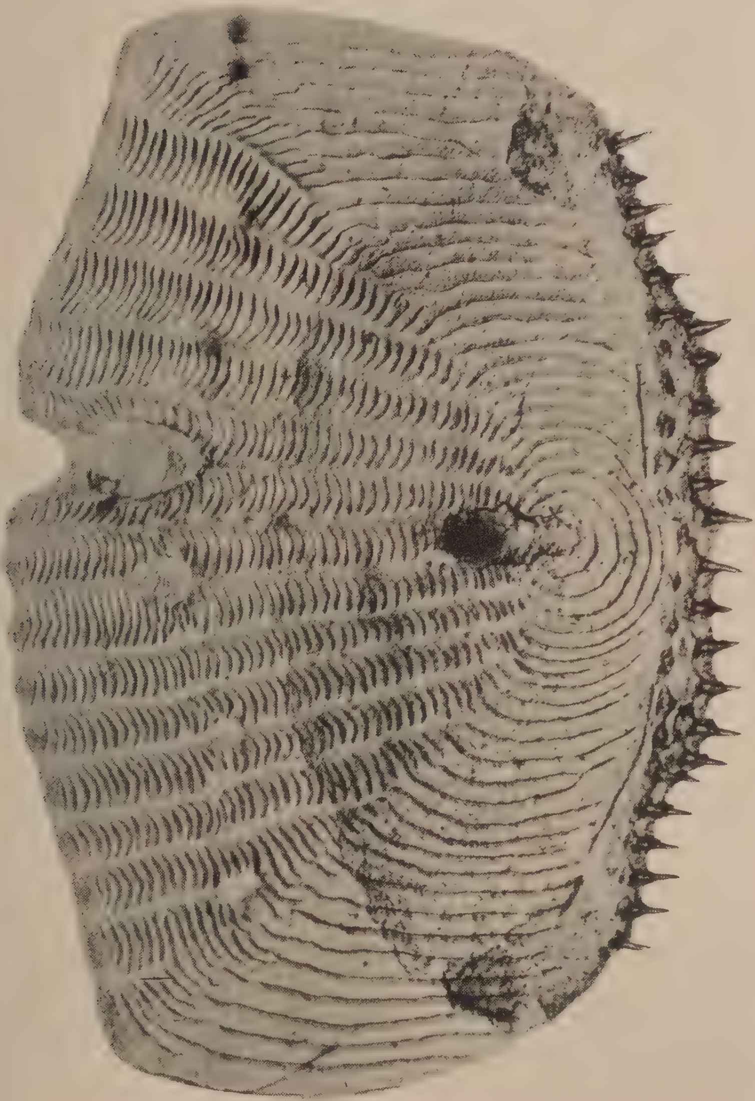


PLATE IV

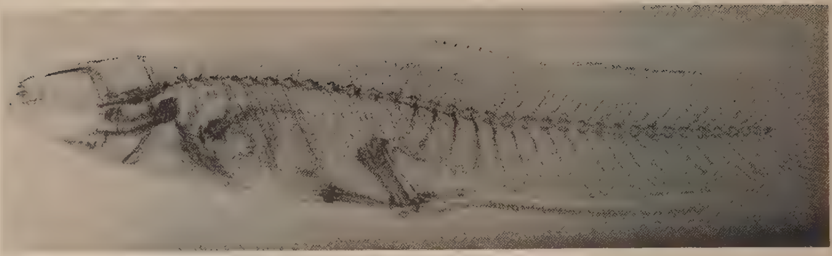
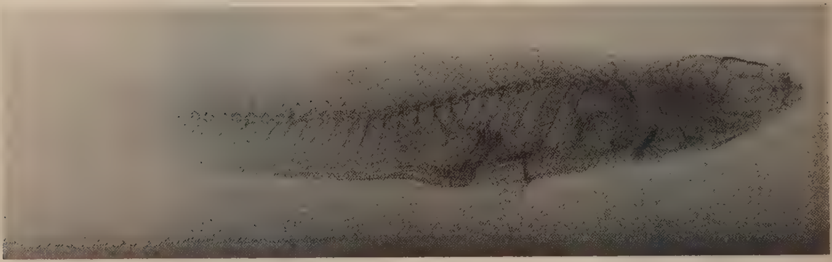


FIG. 1



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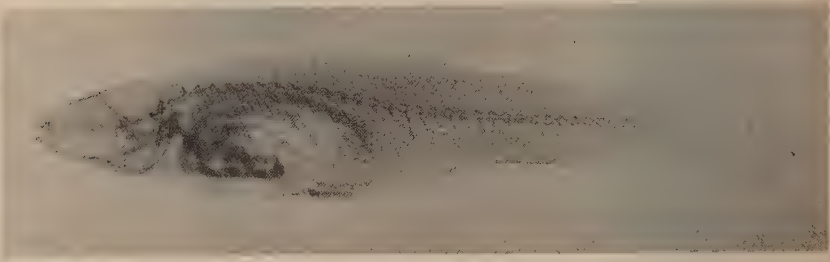

FIG. 3

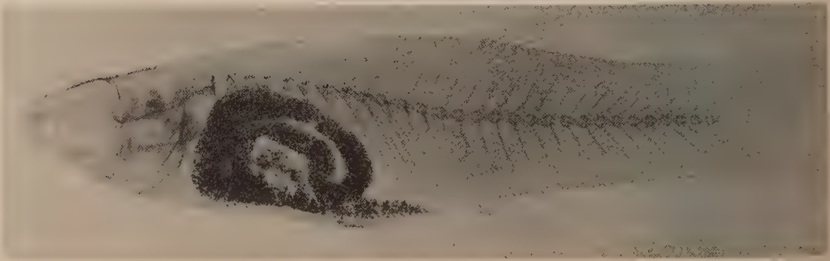

FIG. 4

PLATE IV

X-ray photographs of *Xenodexia* and *Poecilistes.*

FIGS. 1–2. Holotype of *Xenodexia ctenolepis,* a mature male, 40 mm. long.

FIG. 3. Maturing female paratype of *Xenodexia ctenolepis,* 39 mm. long.

FIG. 4. Adult female of *Poecilistes pleurospilus pleurospilus* (Günther), 41 mm. long, collected by Carl L. Hubbs and Henry van der Schalie on February 5, 1935, in Río Michatoya near Palín, Depto. Amatitlán, Guatemala.

Contribution No. 486

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Die Bedeutung der Bakterien für die Erdölbildung

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Wie *A. Treibs* bereits in seinem Aufsatz „Die Entstehung des Erdöls“1) ausführte, sind Bakterien bei der Bildung von Vorstufen des Erdöls aus organischen Rückständen von Pflanzen und Tieren in marinen Ablagerungen maßgeblich beteiligt.

Bakterien in Ablagerungen

Viele Bakterienarten kommen in den Ablagerungen auf dem Meeresboden selbst in einer Meerestiefe von 4000 m vor. Sie wurden aber auch 10 m unter dem Meeresgrund im Boden nachgewiesen, ebenso in Proben von Kalksteinanhydrid-Ablagerungen, die unter keimfreien Bedingungen aus Schwefelquellen bei Tiefen bis 500 m gesammelt wurden.

Bedeutungsvoller ist aber, daß man lebende Bakterien auch in Ölquellen bis zu 3000 m Tiefe gefunden hat. Viele Befunde deuten darauf hin, daß diese Arten in den öltragenden Formationen einheimisch sind, wo sie offenbar sämtliche Bedingungen für Wachstum und physiologische Tätigkeit vorfinden. Die meisten dieser Bakterienarten sind Anaerobier, das heißt, sie leben bei Abwesenheit von freiem Sauerstoff. Neben solchen, die organische Verbindungen einschließlich Kohlenwasserstoffen als Energiequellen verwerten können, gibt es auch andere äußerst genügsame Arten, die selbst mit molekularem Wasserstoff zufrieden sind. Manche von ihnen sind äußerst widerstandsfähig und vertragen Temperaturen bis 95 °C, hydrostatischen Druck bis 600 at, Salzgehalt bis 30% NaCl und p_H 1—10,5.

Hieraus geht hervor, daß manche Bakterienarten in Umweltsbedingungen leben können, unter denen Erdöl in der Natur vorkommt oder seine Bildung anzunehmen ist.

Bakterien produzieren Kohlenwasserstoffe

Schon lange weiß man, daß Bakterien Methan bilden. Es kann durch Zersetzungsvorgänge von organischer Substanz entstehen oder durch Reduktion von Kohlendioxyd durch Bakterien, die molekularen Wasserstoff aktivieren:

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O.$$

Verschiedene Bakterienarten können auch kleine Mengen von Äthan, Propan und anderen gasförmigen Kohlenwasserstoffen bilden, andere auch Karotin, Leprotin, Rhodopurpurin, Flavorhodin und weitere gefärbte Kohlenwasserstoffe der empirischen Formel $C_{40}H_{54-58}$. Diese Verbindungen sind zwar keine Bestandteile des Erdöls, jedoch Beweise für die Fähigkeit zum Aufbau auch komplizierterer Kohlenwasserstoffe.

Die Zellsubstanz von sulfatreduzierenden Bakterien aus marinen Ablagerungen enthält 15—25% ätherlösliches Material, von dem ein Teil aus flüssigen und festen Kohlenwasserstoffen besteht. Zu ihrer Bildung wurden entweder Fettsäuren wahrscheinlich dekarboxyliert, oder sie wurden aus Kohlendioxyd und molekularem Wasserstoff total synthetisiert.

Wasserstoffverbrauchende Reaktionen:

In Erdöllagern kommen mindestens 4 verschiedene Typen von anaeroben Bakterien vor, die molekularen Wasserstoff verwerten können. Dieser stammt entweder von der bakteriellen Verarbeitung organischer Zersetzungsprodukte durch andere Arten, oder von der Zwischenreaktion bestimmter anorganischer Verbindungen wie z. B. Eisensulfid und Schwefelwasserstoff.

Der erste Typ dieser Anaerobier zeichnet sich durch die Hydrierung von ungesättigten Verbindungen wie Linolensäure, Linolsäure oder Hexadecen aus, wobei gesättigte Fettsäuren oder direkt Kohlenwasserstoffe entstehen. Erstere können dann durch Dekarboxylierung in letztere übergehen.

Der zweite Typ katalysiert die reduktive Desaminierung der Aminosäuren durch molekularen Wasserstoff:

$$R \cdot CH(NH_2)COOH + H_2 \rightarrow RCH_2COOH + NH_3.$$

Hierbei entstehen gesättigte Fettsäuren, die wieder durch Dekarboxylierung in Kohlenwasserstoffe übergehen können. Das hierbei freiwerdende Kohlendioxyd kann von einer dritten Art verwertet werden, die es nach der früher wiedergegebenen Reaktionsgleichung zu Methan umsetzt.

Der vierte Bakterientyp reduziert Sulfat mit Wasserstoff zu Schwefelwasserstoff. Durch diese Tätigkeit läßt sich die Erniedrigung des Schwefelgehaltes der Gewässer, die mit Petroleumlagern in Verbindung stehen, ebenso erklären wie das Absinken des Wasserstoffgehaltes der meisten Erdgaslager. Sulfatreduzierende Bakterien synthetisieren beträchtliche Mengen öligen Materials, wozu der Kohlenstoff durch Kohlendioxyd oder die Karbonate der Gesteinslager geliefert wird.

Mikrobiologische Umwandlung des Öls

Alle Arten von Petroleumkohlenwasserstoffen können von Bakterien oder verwandten Mikroorganismen in ihrer chemischen Natur modifiziert werden. Es gibt Lebewesen, die sie vollständig verbrauchen, so daß man sie verantwortlich macht für die Abwesenheit von Öl in Bezirken, in welchen es vorhanden sein müßte. Andere wieder greifen nur ungesättigte Kohlenwasserstoffe an, so daß bestimmte Erdölvorkommen frei von olefinischen Kohlenwasserstoffen sind. Wieder andere Bakterientypen bevorzugen paraffinische Kohlenwasserstoffe, so daß einige Lagerstätten naphthenischen Charakter aufweisen.

Wie bilden sich die Erdöllager?

Bakterien können auch dazu beitragen, das Öl aus öltragenden Materialien freizusetzen, sowie Abfluß und Sammlung in den Reservoiren zu begünstigen. Die wichtigste Tätigkeit ist die Zerstörung von organischem, ölhaltigem Mutterboden, eine weitere die Auflösung von sulfat- oder carbonathaltigem Gestein, an das Öl adsorbiert ist. Dann führten die von Bakterien produzierten Gase, wie Kohlendioxyd, Methan, Wasserstoff und andere, zur Verminderung der Viskosität des Öls und fördern seine Fließfähigkeit.

Diese bakteriellen Prozesse mögen durch alle geologischen Zeitalter hindurch zur Bildung und Wanderung des Öls beigetragen haben.

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1) Die Umschau 50 [1950] S. 233.

BRÖNNERS DRUCKEREI · BREIDENSTEIN · FRANKFURT A. M

Contribution No. 487

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THE POST-NAUPLIAR STAGES OF THE CRUSTACEAN *EUPHAUSIA PACIFICA*[1]

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The marine crustacean *Euphausia pacifica* Hansen is the numerically dominant euphausiid in the plankton of the southern California waters. The later larval stages, particularly, occur frequently in enormous numbers and, as their identity has not been established before, they are often a confusing constituent of the plankton. The main object of this investigation was to establish the sequence of the larval stages of this species and to present them in an easily recognisable form.

The plankton collections made by the *E. W. Scripps* during the plankton surveys of 1940 and 1941 provided most of the material for this investigation. Additional material was collected by the *Quiz-Kid* and the *Paolina T* in 1948. The collections were all made in southern California waters during the spring and summer months.

The nets used were 1 m nets of 24xxx grit-gauze with a cod end of 56xxx grit-gauze, 40 cm nets of number 8 bolting silk and fine-mesh dip-nets. The hauls made by the *E. W. Scripps* were oblique hauls from a depth of 180 m, the remainder being vertical hauls from 700 m, horizontal surface hauls or dip-net samples.

Only a small number of eggs, nauplii and metanauplii was encountered in the plankton, therefore, specific identification of these early stages was not possible. It is hoped to establish positive identification later through rearing experiments. This paper deals therefore with the later larval stages, for it is possible to identify these stages in this species by means of the frontal plate of the carapace which is extremely short and lacks any real rostral processes. Most of the other euphausiids occurring in this area have definite rostral processes which are discernable in the earliest Furcilia stages. The only other form which occurs here and which lacks a definite rostral process is *Nyctiphanes simplex*. This form, however, is readily distinguished from *E. pacifica* by means of the definite emargination of the frontal plate and the process on the basal segment of the first antennal peduncle. These characters, too, are traceable to the early Furcilia stages.

Comprehensive discussions of the works dealing with euphausiid larval development up to 1936 are included in the papers of Fraser (1936) and John (1936). Such a review is therefore omitted from this work.

Following Sars (1885) the Calyptopis stages are defined as the post-naupliar stages in which the carapace still completely covers the eyes.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 487.

First Calyptopis Stage

Plate I, Figs. 1a, 1b. 1c

Length of body about 1.2 mm.

The carapace completely covers the thorax and anterior part of the abdomen Pl. I; (Figs. 1a, 1c). It is dome-shaped and lacks projections or denticles. The median eye is still present and the rudiments of the compound eyes can be seen.

The first antennae are uniramous, unsegmented and carry usually four spines at their distal end. The second antennae consist of an inner and an outer ramus carried by a two-segmented peduncle. The first and second maxillae and first thoracic limb are present and visible below the lateral margin of the carapace without dissection, but are not peculiar in any respect in this or the following Calyptopis stages.

The abdomen or posterior part of the body is shorter than the carapace and the wrinkled integument shows indications of a later segmentation. The terminal portion, which in stage two becomes the telson, is provided with a pair of ventro-lateral spines, three pairs of postero-lateral spines, and six terminal spines which decrease in length toward the center (Fig. 1b).

Second Calyptopis Stage

Plate I, Figs. 2a, 2b, 2c.

Length of body about 1.9 mm.

The compound eyes are more clearly defined than before.

The first antennae consisted of a three-segmented peduncle, but there is yet no trace of flagella. The second antennae and thoracic appendages remain the same as in the first stage (Figs. 2a, 2c).

The abdomen is segmented and the rudimentary uropods can be determined. There is a pair of ventro-lateral spines on the telson, now defined as the last segment of the body, three pairs of postero-lateral spines and seven terminal spines (Fig. 2b).

Third Calyptopis Stage

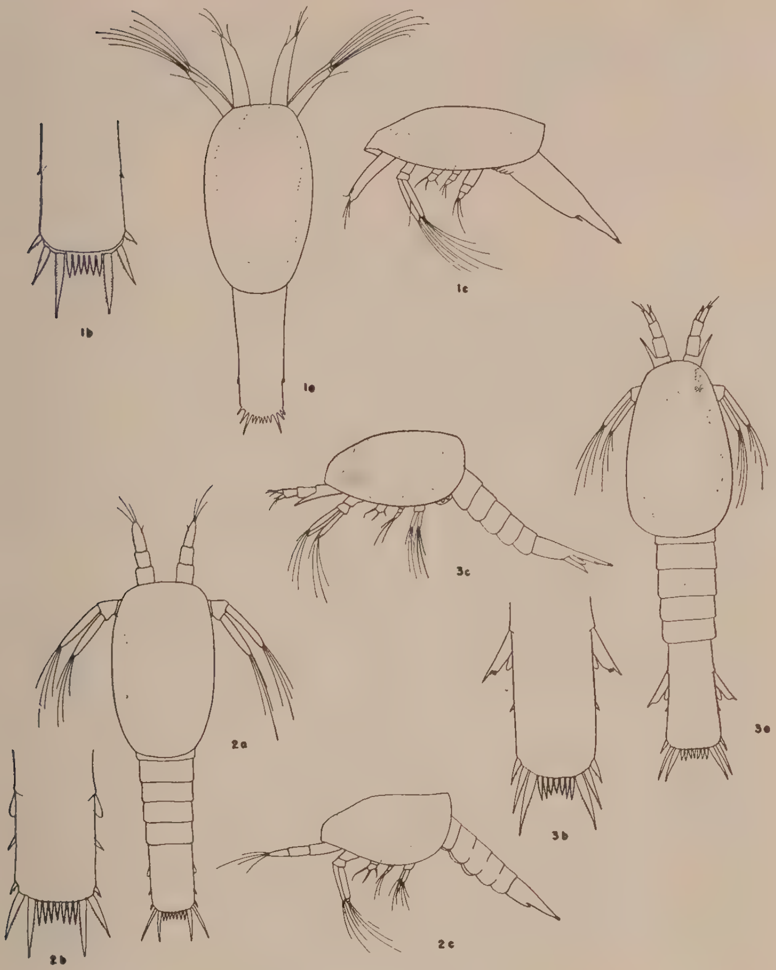
Plate I, Figs. 3a, 3b, 3c.

Length of body about 2.5 mm.

The compound eyes are better developed than in the second stage, now show considerable traces of pigment, but are still completely covered by the carapace (Fig. 3a).

The basal segment of the first antennal peduncle has a strong spine on the outer margin of its distal end which projects beyond the distal end of the second segment. The third segment carries two rounded lobes which are the rudiments of the flagella (Figs. 3a, 3c).

The first three thoracic appendages of the additional appendages are discernable, still enclosed in the integument (Fig. 3a).



Explanation of Plate I

Calyptopis stages of *E. pacifica*

Fig. 1a. Dorsal view of first Calyptopis stage—length 1.2 mm.
Fig. 1b. Posterior end of abdomen showing ventro-lateral, postero-lateral, and terminal spines.
Fig. 1c. Lateral view of same specimen.
Fig. 2a. Dorsal view of second Calyptopis stage—length 1.9 mm.
Fig. 2b. Telson from above, showing rudimentary uropods.
Fig. 2c. Lateral view of same specimen.
Fig. 3a. Dorsal view of third Calyptopis stage—length 2.5 mm.
Fig. 3b. Telson from above.
Fig. 3c. Lateral view of same specimen.

The abdomen is now a trifle longer than the carapace (Fig. 3c).

The uropods are well developed, the outer ramus bearing three short spines distally, while its outer margin is prolonged in a typical strong spine.

The telson carries a small pair of lateral spines, three pairs of postero-lateral spines and seven terminal spines (Fig. 3b).

FURCILIA STAGES

Plates II, III

Fundamentally the methods of identifying the Furcilia stages are those used by Sars (1885) and by Lebour (1924, 1925, 1926, a, b, c, d). However, Fraser's (1936) terminology has been followed and the term "Cyrtopia" abandoned for the later larval stages, i.e. those with the second antennal endopod segmented, and these stages have been included in the Furcilia series. Not only is there a considerable overlap in the length-ranges of the last Furcilia and first Cyrtopia (using the old terminology) but both stages have five terminal spines on the telson. This is the same condition as John (1936, p. 258) found in *E. valentini* and appears to confirm Fraser's view that "too much stress has been laid upon the alteration of form and function of one particular appendange."

Einarsson (1945, p. 8) inclines to the view that if this attitude is taken to the definitions of Furcilia and Cyrtopia phases the same should apply to the change from Calyptopis to Furcilia, and that the logical thing would be to number each stage from the egg to the adult. He does not follow this scheme however, as he considers that it would at first create considerable confusion. While it is true that the change from Calyptopis to Furcilia is also dependent on the change of only one part, the carapace, of the larva, this change is very much more noticeable and results in a complete alteration of the general aspect of the animal. The term Calyptopis has been retained here, too, on the grounds that it facilitates discussion and that its abandonment would result in more, rather than less, confusion.

By including the Cyrtopia in the Furcilia stages Lebour's (1926, c) number of 14 "possible" Furcilia stages is increased to 18 for *E. pacifica.*

MacDonald (1927) first demonstrated quantitatively that certain Furcilia stages tend to be numerically dominant and Fraser (1936) suggested that these dominant stages "should be regarded as the actual stages of that part of the developmental history." There are seven such dominant stages in *E. pacifica.*

Five hundred Furcilia larvae of *E. pacifica* were examined and, as stated above, 18 different types were found. These were identified by the variation in the development of the antennal endopod, by variation in the development of the pleopods, and by reduction in the number of terminal spines on the telson.

A frequency distribution of these forms, plotted as a histogram (Fig. 1), showed seven modes. The modes indicate seven natural groups and these groups represent the seven Furcilia stages of *E. pacifica*. They are as follows:

1st Furcilia—No setose pleopods.
2nd Furcilia—Mixed setose and non-setose pleopods.
3rd Furcilia—Pleopods all setose, 7 terminal spines on telson.
4th Furcilia—5 terminal spines on telson, antennal endopod unsegmented.
5th Furcilia—5 terminal spines on telson, antennal endopod segmented.
6th Furcilia—3 terminal spines on telson.
7th Furcilia—1 terminal spine on telson.

As stated before the main object of this investigation was to establish the identity of the larval stages of *E. pacifica* and to present them in an easily recognisable form, therefore illustrations and descriptions of only the most essential diagnostic characters are given. More elaborate anatomical descriptions were considered to be outside the scope of this paper. In describing the thoracic appendages the term "cormopod" has been used. This includes the maxilliped and the remaining seven thoracic legs.

A diagrammatic key to the Furcilia stages is given in Figure 2, together, with the frequency of the 18 "possible stages." It can be seen that among the instars recognized by the number of terminal spines on the telson, those with an even number of spines have not been allocated to any particular stage. Not only do they occur in exceptionally small numbers but anatomical examination reveals them as abnormal in some respect (cf. Fraser, 1936, p. 52). Even numbers of terminal spines are abnormalities and are not to be considered as variants of the same value as those of the earlier group with unusual numbers of pleopods (John, 1936, p. 257).

It can be seen in Fig. 1 that very nearly half the larvae examined were in the third Furcilia stage. It is probable that the collections examined were made throughout the spawning season, therefore it is unlikely that this is a seasonal effect, and it can be considered as indication that the animals undergo several ecdyses in this stage. There is also an indication that the larvae spend more time in the instar having three terminal spines than in that having five.

First Furcilia Stage

Plate II, Figs. 1a, 1b, 1c, 1d.

In the material examined this instar included forms with no pleopods, or with one, two or three non-setose pleopods. Their frequency is indicated in Table 1.

Table 1. Frequency of occurrence of first Furcilia larvae

Number of pleopods	Number of larvae
No pleopods	3
One non-setose pleopod	9
Two non-setose pleopods	19
Three non-setose pleopods	14

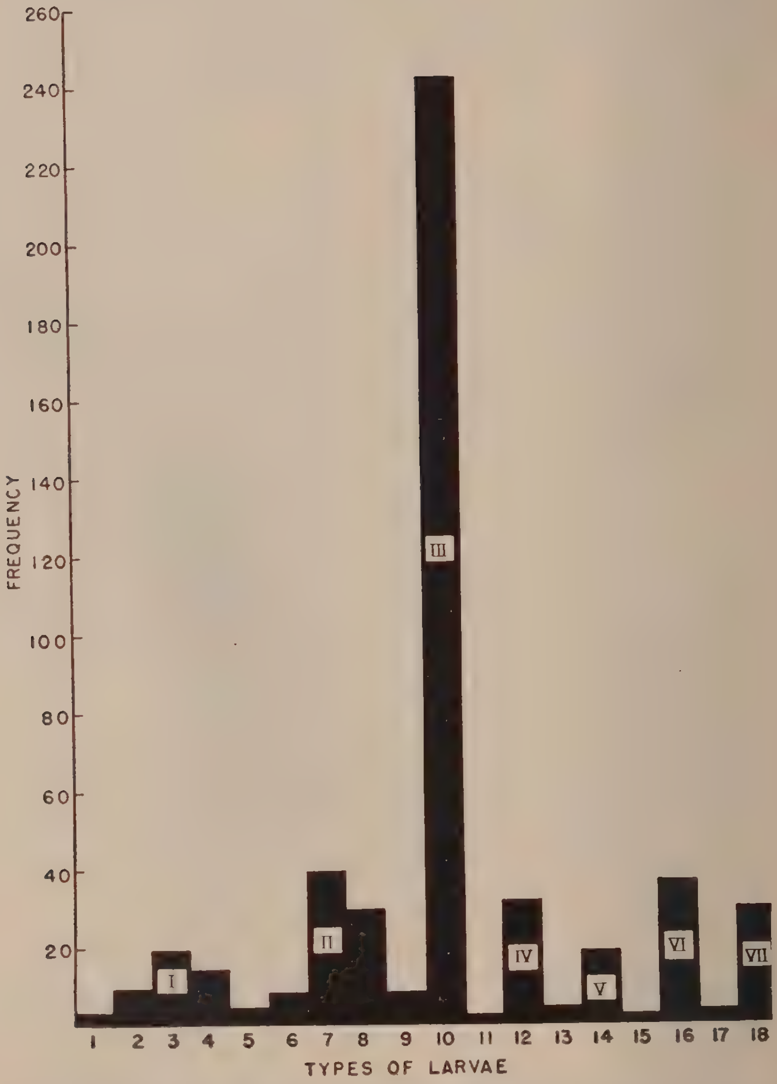


FIG. 1. Frequency distribution of eighteen types of Furcilia larvae encountered. The Roman numerals indicate actual Furcilia stages.

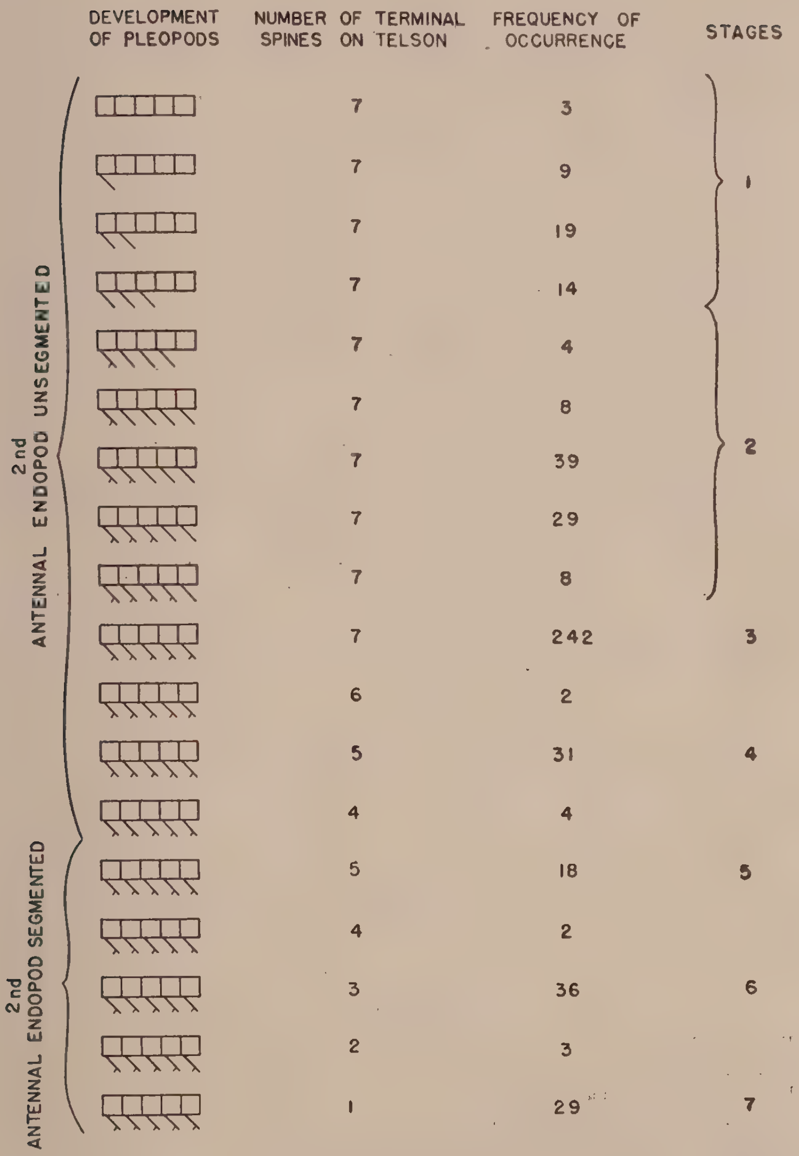

DEVELOPMENT OF PLEOPODS
NUMBER OF TERMINAL SPINES ON TELSON
FREQUENCY OF OCCURRENCE
STAGES
2nd ANTENNAL ENDOPOD UNSEGMENTED
2nd ANTENNAL ENDOPOD SEGMENTED
7 3
7 9
7 19
7 14
7 4
7 8
7 39
7 29
7 8
7 242
6 2
5 31
4 4
5 18
4 2
3 36
2 3
1 29
1
2
3
4
5
6
7

FIG. 2. Diagrammatic key to the Furcilia stages. The five squares forming the rectangle represent the first five abdominal segments—a single stroke represents a non-setose pleopod—a feathered stroke represents a setose pleopod.

The form with two non-setose pleopods is the dominant one and is illustrated in Plate I, Fig. 1. The length range is 3.0–3.2 mm and the average length is 3.14 mm.

Briefly the diagnosis is as follows:

1. There is a single lateral tooth on the carapace toward the posterior margin (Fig. 1a).
2. The first three cormopods are visible, the remaining five being bud-like rudiments (Fig. 1a).
3. There are two non-setose pleopods on the first two abdominal segments (Fig. 1a).
4. The eyes project laterally beyond the anterior margin of the carapace. The anterior margin of the carapace is rounded, somewhat flattened, lacks any rostral projections and extends forward to about the first joint of the first antennal peduncle (Fig. 3b).
5. The second antennal endopod is unsegmented (Fig. 1c).
6. There are seven terminal spines on the telson, with three postero-lateral pairs and a small pair about half way down the length of the telson (Fig. 1d).

SECOND FURCILIA STAGE

Plate II, Figs. 2a, 2b, 2c, 2d

Larvae with both setose and non-setose pleopods are included in this stage. In the material examined several combinations occurred as indicated in Table 2.

TABLE 2. Occurrence of second Furcilia larvae

Number of pleopods	Setose	Non-setose	Number of larvae
4	1	3	4
5	1	4	8
5	2	3	39
5	3	2	29
5	4	1	8

EXPLANATION OF PLATE II

First three Furcilia stages of *E. pacifica*

FIG. 1a. Lateral view of first Furcilia stage—length 3.14 mm.
FIG. 1b. Dorsal view of anterior part of body.
FIG. 1c. Second antennal endopod.
FIG. 1d. Telson and lateral uropods from above.
FIG. 2a. Lateral view of second Furcilia stage—length 3.8 mm.
FIG. 2b. Dorsal view of anterior part of body.
FIG. 2c. Second antennal endopod.
FIG. 2d. Dorsal view of telson and uropods.
FIG. 3a. Lateral view of third Furcilia stage—length 4.3 mm.
FIG. 3b. Anterior part of body from above.
FIG. 3c. Second antennal endopod.
FIG. 3d. Dorsal view of telson and uropods.

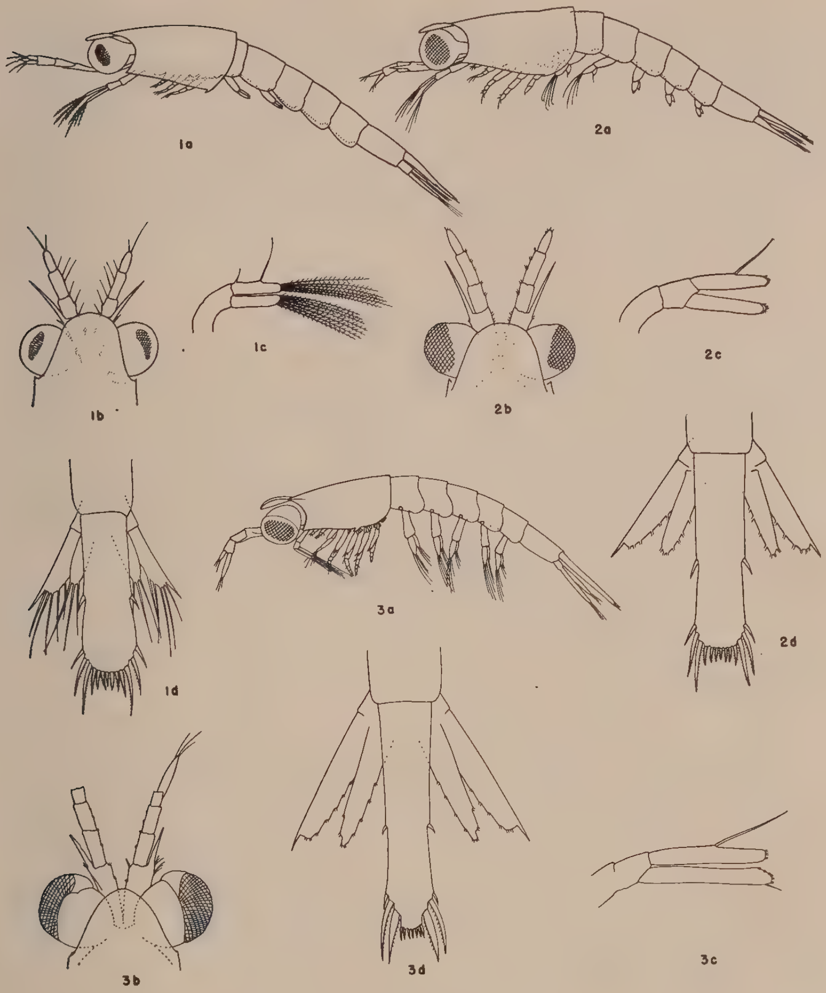


Plate II

It is possible that other variations may be found which did not appear in this material. The form with two setose and three non-setose pleopods dominated and is to be regarded as typical of this stage. Plate II, Fig. 2.

The length range is 3.5–4.1 mm and the average length is 3.8 mm.

In this stage:

1. The full complement of five pleopods has developed, the first two being setose and the remainder non-setose (Fig. 2a).
2. The first four cormopods are visible without dissection (Fig. 2a).

The following points further differentiate this stage from the preceding one. The eyes are larger and the lenses better developed. The anterior margin of the carapace is rounded and does not reach to the distal end of the basal segment of the 1st antennal peduncle (Fig. 2b). The lateral tooth on the carapace is slightly more anterior in position (Fig. 2a). The telson is a trifle longer but is still seven-spined terminally (Fig. 2d). The gill development is more advanced (Fig. 2a). The 2nd antennae, however, are still unchanged (Fig. 2c).

THIRD FURCILIA STAGE

Plate II, Figs. 3a, 3b, 3c, 3d

Of the 500 Furcilia larvae examined, 242 were in the third stage. As stated above, this can be considered an indication that the animals undergo several ecdyses in this stage. The length range is 3.6–5.2 mm, with an average length of 4.3 mm. This long length range is a further indication of several moults in this instar, and indeed the appearance of the shorter individuals differes somewhat from that of the longer. The larger forms are more thick-set, the gill development is more advanced and the flagella of the first antennae are longer. The individual illustrated is of average length.

1. All five pleopods are setose (Fig. 3a).
2. The first five cormopods are visible, the positions of the sixth and seventh being indicated by small gill-buds, and the eighth being quite rudimentary (Fig. 3a).

The following are further indications of development, but not quite so diagnostic.

The eyes are much larger than in the second stage, projecting beyond the anterior margin of the carapace, and having the lenses well developed (Fig. 3b). The 1st antennal peduncle is thicker and the flagella more elongate (Fig. 3b). The 2nd antennae are longer but otherwise unchanged (Fig. 3c). The telson is longer in this stage. It is still seven-spined terminally, but has the modification that the innermost pair of the postero-lateral spines is considerably widened at the base (cf. Fraser, 1936, p. 84), and the outermost pair is relatively smaller (Fig. 3d).

FOURTH FURCILIA STAGE

Plate III, Figs. 4a, 4b, 4c, 4d

Thirty-one fourth stage Furcilia larvae were encountered in the material examined. The length range was 4.2–5.3 mm, with an average length of 4.7 mm. This is the last of the Furcilia stage according to Lebour's use of the term.

1. There are only five terminal spines on the telson, which is longer than in the preceding stage, and the postero-lateral spines are as in the previous stage (Fig. 4d).

2. The first six cormopods are now visible, the ischial and meral segments of the last five being setose on only the anterior margins (Fig. 4a).

In general the anterior margin of the carapace has a far more obtuse-angled projection, while the posterior margin has developed a pronounced emargination. The eyes are not very much larger but they project far more beyond the margins of the carapace (Fig. 4b). All five pleopods are setose (Fig. 4a). The 1st antennal peduncle is better developed, more thickset, more setose, and the flagella are longer (Fig. 4b). The 2nd antennae are also longer and thicker (Fig. 4c).

FIFTH FURCILIA STAGE

Plate III, Figs. 5a, 5b, 5c, 5d

This stage would be the first Cyrtopia stage in the old classification. Eighteen of them were encountered. The length range was 4.5–5.5 mm, the average length being 5.1 mm.

1. The main change is in the 2nd antennae. The antennal endopod is now segmented usually having three segments. The outer ramus has become flattened and scale-like (Fig. 6c).

2. The telson still carries five terminal spines but is a trifle longer (Fig. 5d).

The carapace has the same shape as in the fourth Furcilia, with the frontal plate being, perhaps, relatively a trifle shorter (Fig. 5a). The peduncle of the 1st antennae is much heavier and more setose. The lateral spine of the basal segment projects beyond the distal end of the second segment and carries several spinules on the inner margin (Fig. 5b). The eyes are much the same as in the preceding stage (Fig. 5b). The number of cormopods is the same and remains the same during the animal's life-time. The exopodites are better developed and are setose on their lateral margins (Fig. 5a).

Thus the only real difference between the fourth and fifth Furcilia is the change from a natatory antenna to one with a tri-segmented endopodite and bract-like exopodite, which apparently has no importance in swimming. As there are no significant changes in the form or function of the other appendages, nor any considerable increase in size, it seems only logical to regard this stage as simply a later Furcilia stage.

SIXTH FURCILIA STAGE

Plate III, Figs. 6a, 6b, 6c

Thirty-six of this stage appeared in the material. Sixteen were measured and gave a length-range of 5.0–6.0 mm, with an average length of 5.3 mm.

This instar is essentially similar to the previous one and the complete animal, therefore, is not figured. An outline of the carapace flattened out is shown in Figure 6a. The inner ramus of the antenna has, usually, four segments, and there are three small setae on the distal end of the last segment (Fig. 6b). The three terminal spines on the telson form the most diagnostic feature of this stage (Fig. 6c).

Seventh Furcilia Stage

Plate III, Figs. 7a, 7b

The final Furcilia stage has a length range of 5.3–6.5 mm, and an average length of 5.9 mm. There were 29 of them in this material.

The main differences to note are the length of the antennal endopod, which usually has eight segments at this stage, and the outer bract which carries more spines on its inner margin (Fig. 7b). The telson has only one terminal spine, but the postero-lateral spines are as yet unaltered (Fig. 7a).

Juvenile Forms

The juvenile is distinguished from the Furcilia by means of the telson, which has a single terminal spine but only two pairs of postero-lateral spines. By this time the animal has undergone its major developmental changes, and the adolescent merges imperceptibly into the adult. It was not possible to find any definite stages among the juveniles, for considerable individual variation exists. As pointed out by Rustadt (1930) and Bargmann (1936) sexual maturity may be attained before the animal has reached its adult form.

Summary

Euphausia pacifica passes through ten post-naupliar stages. The first three of these are Calyptopis stages and the remaining seven are Furcilia. These stages are described and a key to the Furcilia stages is included.

Explanation of Plate III

Last four Furcilia stages of *E. pacifica*

Fig. 4a. Lateral view of fourth Furcilia stage—length 4.7 mm.
Fig. 4b. Anterior part of body from above.
Fig. 4c. Second antennal endopod.
Fig. 4d. Dorsal view of telson and uropods.
Fig. 5a. Lateral view of fifth Furcilia stage—length 5.1 mm.
Fig. 5b. Dorsal view of anterior part of body.
Fig. 5c. Second antennal endopod showing segmentation.
Fig. 5d. Telson and uropods from above.
Fig. 6a. Second antennal endopod of sixth Furcilia stage.
Fig. 6b. Flattened-out carapace of a specimen 5.3 mm long.
Fig. 6c. Dorsal view of telson and uropods.
Fig. 7a. Telson and uropods of seventh Furcilia stage.
Fig. 7b. Second antennal endopod of same.

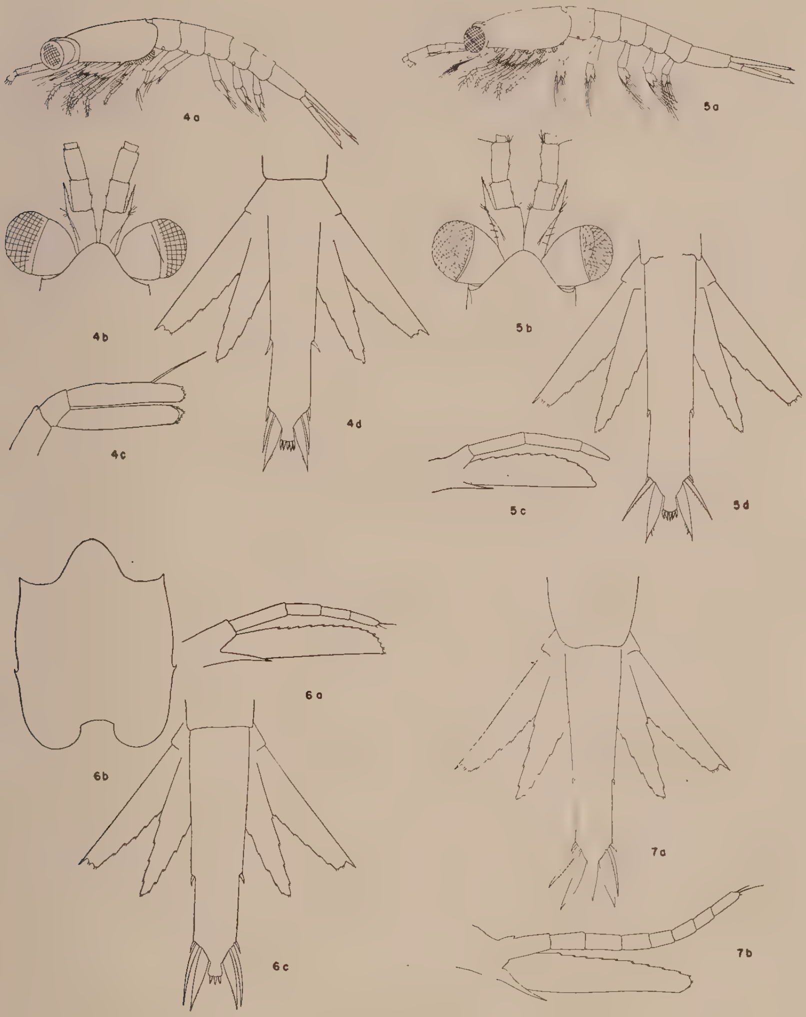


PLATE III

ACKNOWLEDGMENTS

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Contribution No. 488

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The Fluorescing Substances of an Intertidal Ocean Mud[1]

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INTRODUCTION

A chromatographic analysis has been carried out with an intertidal mud sample scraped as a layer about 3 in. thick from the surface of exposed flats on the north shore of the relatively protected inner arm of Mission Bay, San Diego, California. Like the deep-sea material investigated earlier (age up to 960 years) (1) this fresh mud of recent history gave bluish-gray fluorescent fractions but it failed to yield detectable amounts of phytofluene (2). A comparison of Fig. 1 with the corresponding curves obtained from our deep-sea mud (1) shows that the two sets of fluorescent compounds must be different.

The fresh mud sample also contained several carotenoids aggregating a weight of about 0.2 mg./kg. of dry material. Of these, the preponderant fraction showed epiphasic behavior, thus agreeing with data published by Fox *et al.* (3).

EXPERIMENTAL

The starting material was a 20-kg. sample which was transported under methanol. The original water content was 55%; the organic matter content of the dry mud as determined by the chromic acid method averaged 1.85%.

Procedures for extraction and saponification have been described earlier (1). The methanolic alkaline layer was dark and showed the red fluorescence characteristic of chlorophyll and some derivatives.

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[2] Publication No. 1480.

[3] Contribution No. 488 (new series).

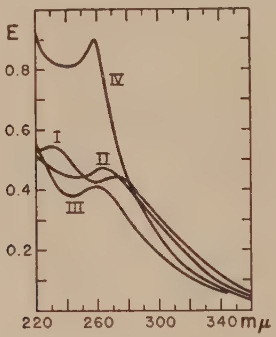

Fig. 1. Spectral curves in hexane of some fluorescing compounds contained in an intertidal ocean mud sample.

The resulting, partly purified extract was developed with petroleum ether containing 3% acetone on four columns (28 × 7.5 cm.) of calcium hydroxide + Celite, 3:1. In the following chromatogram the figures on the left denote the height of the zones in millimeters, while those on the right (in parentheses) designate mg. pigment/kg. dry material:

4 Reddish-brown (0.0025)
2 Orange (0.0025)
2 Red (0.01)
3 Yellow (0.005)
10 Colorless, weakly fluorescing (no typical spectrum)
7 Pale pink (0.006)
15 Colorless, strongly fluorescing: compound I
30 Colorless, weakly fluorescing (no typical spectrum)
5 Yellow (0.04)
5 Colorless, fluorescing: compound II
15 Orange, β-carotene (0.13)
20 Pale yellow (overlapping), strongly fluorescing: compound III
2 Yellow
15 Colorless, strongly fluorescing: compound IV

When individually partitioned between petroleum ether and 90% methanol, only the two top zones showed hypophasic behavior. The ratio of hydrocarbon carotenoids to xanthophyllic compounds would appear to be nearly 40:1.

Each of the principal fluorescing compounds (I–IV) was re-chromatographed several times before the readings on the Beckman spectrophotometer were taken (Fig. 1).

SUMMARY

The observed fluorescence of crude and purified extracts of a fresh, intertidal ocean mud sample from the Pacific Coast was caused by four colorless, chromatographically separable compounds which showed extinction maxima around 260 mμ, in hexane. Phytofluene or a similar fluorescing polyene was absent.

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Contribution No. 489

parency has been attained in several ways: the wing s may be reduced in size, or in number, they may l up on edge, or they may themselves be trans- nt; while in clear-wing moths which mimic wasps cales are loosely attached and are lost soon after rgence from the chrysalis. It is also significant mimetic resemblances only affect superficial or le characters: in other words, the effects are essen- external and such as appeal to the eye. H. B. C.

UCTURAL COLOURS AND PIGMENTS OF ANIMALS

ne causes of colour in animals are (1) the fraction of reflected light and (2) the absorption, by nically unsaturated molecules, of one or more ons of the visible spectrum. The fractionation complished chiefly through either interference, or ering by very minute physical structures of nsions approximating to the wavelengths of le rays; thus we observe physical, optical or struc- colours. Absorption, on the other hand, is ned through internal frictional processes between waves and electronic vibrations of similar fre- cies. Molecules which, regardless of their ical orientation, thus convert light into heat, re- ng or transmitting the unabsorbed residue of , are the pigments.

ctural Colours.—The physical effects of certain ctures, giving total reflection (white), interference escent or changeable coloration) or scattering ndall blues or violets), all of common occurrence ne inanimate world, are likewise responsible for ar conspicuous colour effects in animals.

hite Aspects.—Equal and complete reflection of ered white light may arise from any of several s of structures encountered in animals. Com- ly the effective structures are microscopic air es that separate finely divided keratin material in e feathers, in white fur or hair, and in the white s of some butterflies and moths. Secretory or r deposited material from animal tissues may larly scatter white light, contributing like effects; nples are (1) emulsified lipid materials; (2) chalk ther calcareous materials in molluscan and foraferan shells, in crustacean carapaces and in the etons of echinoderms and corals; (3) silica in ges; (4) colloidal protein in serous membranes; vhite crystalline pterins in wings of butterflies; and silvery deposits of purines in some invertebrates, kins of amphibia and in scales of fishes.

idescent Colours.—Fractionation of white light into spectral components is accomplished in animal ctures principally through interference. This lves the penetration and return of the light through nerous very thin superposed films or laminations. returning rays, reflected from different depths and through various total thicknesses, suffer rhythmic lacements, by mutual cancellations and reinforce- ts, of their characteristic waves in such a manner result in interference. The net effect is a striking escence.

oap bubbles and oil films upon dirty water or wet k pavement provide some of the best examples of e iridescent colours, first scientifically described in form of rings between pressed layers of glass by Isaac Newton. These colours, changeable with angle of incidence or observation, are very com- in animal structures. Outstanding examples are arresting blue to violet wing scales of the South erican *Morpho* and other butterflies, the brilliant escent hues encountered in feather barbs of pea- ks, humming birds and many others, the elytra of ntless beetles, the wings of some lacewing flies, the er skin of snakes, nacreous layers of calcium carbo- in pearls and mother-of-pearl, bristles of certain ine worms, e.g. *Aphrodite*, and the brilliant lustre given in sunlight by the minute scales surrounding human or other mammalian hairs. The brilliant iridescence of such structures as bird feathers and beetle elytra is fortified by the absorption of the most deeply penetrating light by layers of the black pigment melanin beneath the chromogenic laminated structures.

Tyndall Blues.—Non-pigmentary blue colours due to the Tyndall effect (q.v.) are common in both the inanimate world and the living kingdom.

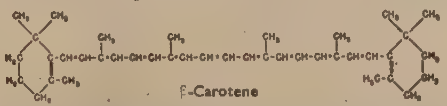
The Tyndall blues are widely observed in animals chiefly where a turbid, light-scattering medium overlies a dark melanin substratum which serves as an effective absorbing screen for the longer penetrating wave-fractions. Purity is thus imparted to the scattered blue component reflected from the upper, unpigmented layers. In blue eyes the practically colourless, turbid, blue-light-scattering stroma of the iris is lined beneath by the deeply pigmented uveal membrane, an effective light screen. In brown or black eyes, the melanin pigment is present also in the iris. Other examples of Tyndall blues are the striking cerulean areas of skin upon the face, scrotum, buttocks etc. of baboons and other primates, also those about the head and neck of turkeys, guinea fowl, cassowaries and the like, and the transitory blue sacral skin-patches or 'Mongolian spots' of oriental infants. The gorgeous blues seen in the skin of numerous reptiles and fishes arise in a like manner. Outstanding examples of these biological Tyndall blues are encountered in the blue feathers of many birds. In feathers (q.v.) the blue colour is scattered by countless sub-microscopic air spaces that separate the keratin matrix overlying black deposits of melanin in the cortex of each barbule. In the eyes and skin of vertebrates, however, the blue-scattering particles are mostly minute protein micelles in an aqueous medium. In fishes and reptiles the effects are augmented by the presence of sub-microscopic particles of guanine or other purines.

If light is to be fractionated, either by interference or by scattering, the responsible elements, laminations or colloidal particles respectively, must be of the order of 0·4 to 0·7 μ in thickness or diameter, thus falling within the wave-length of visible light. If the laminations, e.g. of calcium carbonate, be thicker, as in many shells, or if the dispersed particles exceed these dimensions, as do the air vesicles in numerous white feathers, then the light is reflected equally and totally, giving white aspects rather than the respective chromatic effects. Green feathers or green patches of reptilian or fish skin often result from the vertical juxtaposition of a structural blue and a pigmentary (e.g. carotenoid) yellow.

Air-produced whites or Tyndall blues of feathers may be gradually discharged by saturating the structure with a fluid, such as cresol or phenol, having a refractive index very similar to that of the keratin matrix (1·54). Under such conditions the barbules of white feathers become nearly invisible in the fluid, while those of blue feathers turn black. The original appearance is readily restored when the foreign fluid is replaced by air.

Pigments.—These may be carotenoids, tetrapyrroles, indoles, purines, pterins, flavines, quinones, flavones, anthocyanins and others.

Carotenoids.—Living organisms from bacteria and other simple types to the most complex flowering plants, and from protozoa to man, contain, with few exceptions, varying amounts of yellow, orange or red carotenoids, usually either dissolved in fat droplets or chemically associated with proteins. Insoluble in


β-Carotene

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water, the protein-free pigments may readily be dissolved in ordinary fat-solvents such as alcohol, acetone, ether or chloroform. They possess definite and characteristic crystalline habits, and when dissolved, show well-defined absorption bands in the violet to blue spectral regions. Possessing a high degree of chemical unsaturation, they are readily bleached by light, atmospheric oxygen or other oxidizing agents, and are decomposed by strong mineral acids, often with transient manifestation of blue colours.

Mammals as a class are not rich in carotenoids, although they require vitamin A (derivable from carotenes and a few other members of the group) for successful growth, reproduction, vision and the maintenance of mucous and integumentary surfaces. Horses and cattle, unlike sheep, goats, swine, rabbits and carnivorous mammals, carry fairly rich stores of carotenoids in their blood serum and various organs, especially when feeding in green pastures during the spring. Ovaries (corpus luteum), some testes, liver, adrenals, blood, eyes and milk are carotenoid depots, and the skin of the leg, the body fat and eggs of domestic poultry and other birds are also often conspicuously pigmented by these compounds. The bright yellow, orange or red feathers of numerous birds, similar hues in wings or elytra of many insects, and the yellow colours of butter and some animal waxes are manifestations of these pigments.

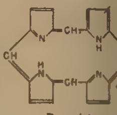
Among the lower vertebrates, the familiar colours of carotenoids are displayed most extravagantly and brilliantly in the integument of certain amphibians (e.g. salamanders) and of countless species of fish. Rich and varied colours and colour-patterns arising from this class of pigment are also to be seen in the invertebrates, notably among the crustaceans (crabs, lobsters, shrimps), echinoderms (starfish, brittle stars), molluscs, tunicates (simple and compound sea-squirts), coelenterates including anemones and corals, and various marine worms. Within the echinoderm, crustacean and a few molluscan groups, especially, are to be seen gorgeous blue, violet and green hues, and more sombre grey, chocolate or nearly black tones, all brought about by chemical combinations between carotenoids and proteins. Boiling water or alcohol denatures the protein portion, thus producing a colour change to that of the carotenoid (e.g. the familiar change from blue to red of boiled lobsters). Like the land fauna, aquatic animals derive their rich carotenoid pigmentation ultimately from plant sources. Many carnivorous and mud-eating animals from the vast, unlighted depth of the ocean owe their integumentary carotenoids to supplies originally generated by plants in the upper lighted waters. Such plant materials are later eaten by herbivorous or omnivorous prey, or alternatively buried in the sediments of the ocean floor. Chromogenic bacteria and fungi may also contribute to this source of supply.

Many animals are specifically equipped for the assimilation of the hydrocarbon (carotene) variety of carotenoid, whereas countless others are adapted to accumulate only the oxygenated (alcoholic or xanthophyllic) kind, wherein hydroxyl groups are linked to one or both terminal cyclohexenyl rings. The horse, for example, absorbs in its intestinal mucosa and transfers thence to the blood stream only the carotenes, although it consumes green food containing more xanthophylls than carotenes. Certain marine worms and sponges exhibit the same kind of selectivity on natural diets of sedimentary detritus containing more of the xanthophyllic type of carotenoid. The hen and other birds, and many species of fish and invertebrates, on the other hand, store only xanthophyllic carotenoids, expelling the carotenes in their faeces or otherwise disposing of them. Other organisms, including octopus, frog and man, assimilate both kinds, storing them in the body fat. Pigs assimilate no
coloured carotenoids in their liver, blood or adip
tissues.

Females of many animals (e.g. hens, fishes) accum
late carotenoids in their developing eggs during
reproductive season. As a result, there is a noticea
gradual paling of yellow colour in the skin. Males
the same species may continue to exhibit or even a
ment their integumentary yellow pigmentation at su
seasons.

An unusual transitory and non-pathogenic yello
ing of the skin, termed xanthosis, carotenemia or a
ficial jaundice, may result from excessive consumpt
of carotenoid-rich foods, such as oranges or carro
The condition is less frequently seen in adults than
children, and gradually disappears on resumption o
more normal diet. This temporary yellowing is
to be confused with the characteristic colours of ori
tal skins, which owe their tints to the presence of dil
melanin in the epidermis.

Tetrapyrroles.—In this class are included the deri
tives of porphin and of bilin.



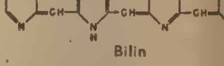
Porphin

(1) Porphin derivatives. Porphin, the closed ch
of methenyl-linked pyrrole nuclei, constitutes
basic chemical skeleton of all the nitrogenous, water-soluble pigments under discussion in this section. Side chains of varied length and character, made up of carbon, hydrogen and sometimes oxygen, bonded to different carbon atoms of the four constituent pyrrole groups of porphin, give the porphyrins,
commoner examples of which form the basis of
green, photosynthetic, magnesium-containing chlo
phylls of plants, and the red, iron-bearing, oxyg
carrying haemoglobins of many animals. Haemog
bins characterize the red blood cells of all vertebr
animals and are present also, usually in solution, in
circulatory fluids of some invertebrates, notably m
worms. Scattered members of the arthropod, echi
derm and molluscan phyla possess haemoglobins.

Whilst the protein (globin) portion of the molec
differs from species to species the porphyrin conjuga
haem, is common to all haemoglobin-bearing anim
This class of pigment combines reversibly with atm
spheric oxygen in the lungs of air-breathing vertebra
in the gills of fishes and larval amphibia, and in ot
respiratory surfaces of worms etc.; thus serving
maintain a supply of the dissolved gas to the tissu
Haemoglobins confer the familiar pink or red colo
of naked skin patches on the combs and wattles
birds and on the facial, buttock and genital region
primates. The skin and flesh of numerous wor
show the pink tint of haemoglobin.

Among other porphyrin derivatives are cytochro
an essential intermediary in the oxidation processes
many cells; catalase, the hydrogen peroxide-deco
posing catalyst in cells; chlorocruorin, a green ir
haem protein serving the respiratory needs of so
tube-building annelid worms; and red helicoru
encountered in the gut and liver of certain snails.

Porphyrins are responsible for the colours of
egg-shells of certain birds, and are present in so
molluscan shells. Turacin, a red copper-porphy
is secreted by the African turaco into its quill feathe
turacoverdin is a similarly occurring green oxida
product of turacin.



Bilin

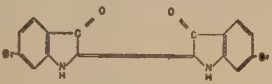
(2) Bilin derivatives. Haem pigment may be decomposed in the animal's metabolism, with the loss
of one inter-pyrrole linking methenyl group, to yi
non-metallic open-chained members of the tet
pyrrole class belonging to the bilin series. Th
are yellow, red, blue, green or brown water-solu
pigments of varied distribution in animals
their tissues. Small amounts of the common

pound, bilirubin, its green dehydrogenation luct, biliverdin, and a number of other similar pounds occur in normal tissues and may impart picuous colours to pathological urines or secretory erials. Such compounds are recoverable in rela- y large quantities from mammalian bile.

arious derivatives of the bilin class occur in birds other animals. Oöcyan, akin to biliverdin, con- blue or blue-green colours upon the egg-shells of a ber of birds. Biliverdin has been reported in the l of the emu egg, in the skeleton of the blue coral *opora caerulea*, and is suspected in the green or -green bones of certain belonid and cottid fishes. obilin is a blue compound found in the wings of e pierid butterflies. Other insects and their larvae osit or excrete similar bilins. Some leeches, sub- ng upon the blood of vertebrates, carry in their and hepatic cells blue-green, red or brown bilins ch are presumably degradation products of the sted haemoglobin. Additional examples include liverdin-like compound in the green base of the of *Actinia equina* and other sea-anemones; dark or violet calliactine in the anemone *Calliactis para- a*; the red pigment rufine in the slug *Arion rufus*, scine in some abalone (*Haliotis*) and turban shells rbinidae and Trochidae), and the respectively et and red aplysioviolin and aplysiorhodin (for- ly referred to collectively as aplysiopurpurin) he purple, mucous secretion of the sea-slug *ysia*.

dole Derivatives.—Under this heading the indi- s and the melanins, both of which are chemical vatives of the same basic compound, indole, are idered in this order, thus proceeding from the ively simple compounds of restricted distribution e incompletely known chemical complexes which art the sombre colours to many animals and contri- to the formation of some brilliant colours.

) Indigoids. The best-known example of this class is indigotin, indigo-blue. It occurs as a oside in many tropical plants, long exploited for pigment, which is used commercially as a blue dye. le indigo itself is of very limited occurrence in nals, allied substances are encountered in certain etory and excretory materials. Tyrian purple is a omindigo, occurring in the hypobranchial gland several marine gas- ods belonging to the ra *Murex* and *Pur-* . ndigo blue, indigo red irubin) and indigo green are sometimes shown athological human urine on oxidation by air, or e easily, especially in the case of the blue homo- e, by applying the indican test (mild oxidation chlorates or ferric salts and subsequent extrac- of the pigment with chloroform). Spectro- ically, the indigoid pigments, when dissolved in nic liquids, exhibit in the visible range of light picuous absorption bands.



Dibromindigo

) Melanins. Various pale yellow, buff, tawny, ly, brown, grey or black colours of eyes (iris), gument, scales, feathers and numerous internal nbranes or organs are due to the presence of mela- in any of several stages of oxidation or in relative ees of physical (colloidal) dispersion. The pig- ts of brown or black skin-moles, melanotic ourous growths and the ink of cephalopod uscs (e.g. sepia of commerce) are melanins.

ielanins are refractory end-products of metabol- synthesized by animals as a result of progressive ation, with polymerization, of the amino acid sine or allied phenolic compounds. A special me, tyrosinase, catalyzes this oxidation by dis- ed atmospheric oxygen, the substrate progressing ugh chemically reversible yellow, orange or reddish stages to an ultimate irreversible, intensely black end-product. The foregoing reactions, observable in the laboratory, do not always proceed to chemical completion in the bodies of animals; hence we see manifested the various non-black melanistic hues mentioned above.

Certain white or albino animals may actually lack the essential enzyme in its active form, or they may maintain both enzyme and substrate separate from one another. Numerous melanin-free plant and animal tissues, for example, such as apples, potatoes, and white or red variants of the plumose anemone *Metridium senile*, show a rapid formation of dark melanin when cut, ground or macerated in air.

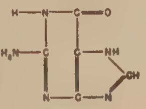
Genetically or environmentally induced melanization (sun-tanning) of the skin may serve a useful function in screening out injurious short-waved fractions of sunlight from the sensitive underlying tissues.

When maintained on dark rather than on pale backgrounds, even when receiving the same illumination from above, certain fishes and amphibia possess an interesting capacity for the slow synthesis and storage in their skins of increased quantities of melanin in addition to the quick adaptation to the background tint by means of chromatophores.

Although melanins occur most widely in vertebrate animals, they may be observed in the integument of many invertebrates as well, notably among the insects and to a lesser degree in crustaceans, molluscs, flatworms and coelenterates.

Urochrome, the conspicuous yellow pigment of urine, is of unknown nature but is considered by some to belong to the melanin class. Its excretion increases during fever or other wasting illnesses. In certain disorders, melanogenic substances are excreted in the urine, causing it to darken on standing in air (alkaptonuria or melanuria).

Purines.—Members of this class, being white, are perhaps hardly to be grouped under the true pigments, but they are included here because they frequently contribute to the colour-patterns of lower vertebrates and many invertebrates.



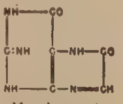
Guanine

Fishes display whiteness or brilliant silvery iridescence in their scales and in areas of skin, due to the deposition therein of minute guanine crystals. Some are capable of gradually varying the quantities of white integumentary guanine in proportion to the whiteness of the backgrounds upon which they live.

Many insects, notably certain pierid butterflies, deposit xanthine and other purine derivatives in their wings. Uric acid has been encountered in the white mesenteries of the anemone *Metridium senile* and in the yellow sheets of mucus secreted from its mouth. Guanine is conspicuous as a white, powdery component of birds' excrement (e.g. commercial guano).

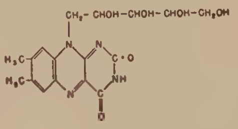
Pterins.—These compounds, chemically akin to the purines and formerly classified with them, are encountered as white, yellow, orange or red granules in the wings of certain butterflies. They are responsible also for the yellow body-colour of numerous wasps. Pterins are soluble in watery media, especially in the presence of alkali, and are insoluble in the common organic solvents.

Leucopterin, a white compound, has been isolated from the wings of pierid butterflies, while xanthopterin is a yellow pigment in the wings of other Lepidoptera and in the abdominal integument of certain wasps. Whereas the red pigment in the eyes of the fruit-fly, *Drosophila melanogaster*, of great interest to geneticists, is believed to be related to the pterins, no known physiological functions have yet been established for these substances.



Xanthopterin

Flavines or Lyochromes.—Under this heading is included a limited group of yellow, greenly fluorescent water-soluble pigments. Although of very wide distribution in tissues of plants and animals, the flavines exist there in such minute quantities that their colours are inappreciable until they have been extracted chemically. The prominent member of the series is lactoflavine or riboflavine, identical with vitamin B_2 (G). Animals are generally incapable of its synthesis, and therefore depend directly or indirectly upon plants for their supply.

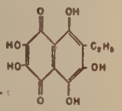


Lactoflavin

The 'yellow oxidizing enzyme' of Warburg is composed of lactoflavine conjugated with a protein. The yellow colour, developing when the enzyme combines with oxygen, vanishes when this element is released for intracellular oxidative processes. This catalyst is present in various tissues. Its absence from the diet leads to cellular respiratory disorders, retardation of growth and various physiological disturbances in birds and mammals.

Quinones.—The animal quinones comprise naphthoquinones and anthraquinones.

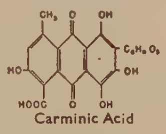
(1) Naphthoquinones. Red, purple, orange, yellow or green compounds of this category are encountered in many plants, from which they may be extracted with organic solvents. Certain of them have been used as dyes for fabrics. They rarely occur in animals and are apparently limited to sea-urchins. Many such species display conspicuous amounts of naphthoquinoid echinochromes in their thin skin and in the calcareous material of spines and shells, which thus assume red, purple, pink or greenish colours. Red or purplish aggregates of such pigmentary materials are encountered also in the blood cells, gut-wall and eggs of some species. As in the case of other quinones, echinochromes oxidize certain chemical reducing agents with accompanying loss of their own colour. Their coloured solutions exhibit absorption bands in the green, blue and violet regions of the spectrum. In watery solution they are red in acid, purple in alkali.



Echinochrome

No definite physiological role of echinochromes has been established although vitamin K, the anti-haemorrhagic factor, is a naphthoquinone. It seems probable that the echinoids assimilate their quinones from the plants in their diet.

(2) Anthraquinones. Like the naphthoquinones, to which the anthraquinones are chemically similar, brilliantly coloured members of this group have been employed extensively as dyes, and may be utilized as chemical indicators of acidity or alkalinity. A well-known example of animal anthraquinones, doubtless derived from plant diets, is carminic acid, the bright-red compound forming some ten per cent. of cochineal, extracted from the female scale insect *Coccus cacti*, native to Mexico and Central America. Another such pigment is kermesic acid, found in *Coccus ilici*. Its yellow-red aqueous solutions are rendered violet-red by the addition of acid. It is closely similar chemically to carminic acid and, like the latter, is employed as a dye. From the solid exudate of the Indian lac insect, *Coccus laccae*, is recovered a scarlet or carmine-red dye, laccaic acid, chemically akin to the former two compounds. It is not yet known whether these nutritionally derived anthraquinones may be of physiological value to the insects which secrete them.



Carminic Acid

Flavones and Anthocyanins.—The flavones (also called xanthones or anthoxanthones) are, as suggested by their names, yellow in colour. They have receive much chemical study, are phenyl derivatives of th chromone or benzo-γ-pyrone nucleus and occur in great variety of plants. Their presence in anima seems to be limited to a few insect species whic assimilate them from plant food. The wings of th Marbled White satyrine butterfly, *Melanargia galate* for example, yield an ethanol-soluble yellow flavon chemically similar to quercitin and found also in th cock's-foot grass, *Dactylis glomerata*, on which th larva of the insect feeds. Flavones have been su pected in certain hemipterous insects, in some speci of silkworm and in a few hydroids.

The chemically allied anthocyanins are violet, red blue derivatives of the γ-pyran or benzopyranol con pounds, and are displayed extravagantly in petal fruit and leaves of numerous plants. Like the flavon their occurrence in animals is rare, and is probably co fined to a few insect species, notably in the albumino inclusions of fat cells in certain dipterous and hem pterous forms and their larvae. While the anth cyanins may perhaps play a part in biochemic oxidations in the plants which synthesize ther their presence in the animal consumers is probab fortuitous.

Miscellaneous Pigments.—A large number of anim pigments possess molecular constitutions which are yet imperfectly known. Of these only a few relative outstanding representatives will be cited.

Chromolipoids or lipofuscines belong to a group fat-soluble yellowish, ruddy brown or even black pi ments observed in fat droplets of eggs and other rel tively fatty cells and tissues. Because of their colou the chromolipoids have often been confused with bo carotenoids and melanins. They are presumably d rived from partially oxidized fats, phospholipids, fat acids and other lipoid compounds. The chromolipo pigments tend to increase in amount, in degree oxidation and in depth of colour with the advanci age of an animal.

Haemocyanins are the oxygen-carrying pigmer found in the blood plasma of some crustaceans a molluscs. Colourless in the chemically oxygen-fr state, haemocyanins assume a blue colour upon co bination with oxygen. The oxygen is ultimately r leased, during circulation, to the tissues requiring Haemocyanins are composed of large protein co plexes, conjugated with copper, which is responsib for the blue colour of the oxygenated phase.

Haemerythrins are iron-containing, protein bloo pigments of gephyreans and certain polychaete worn Serving as chemically reversible oxygen transporte like haemoglobins and haemocyanins, haemerythri are of a pale straw-colour in the reduced state, beco ing reddish when oxygenated.

Vanadium chromogens are encountered as blue, gre or orange granular bodies within the blood corpusc of tunicates. The various colours reflect the fact th the involved protein is conjugated with vanadium various oxidative stages.

Numerous animals exhibit brilliant colours due the presence of pigments of yet unknown chemi nature. Examples may be seen in the permanent r skeletal pigments of such corals as *Corallium rubr* and *Tubipora musica*, and the colours of many spong annelids and tunicates. D. L. F.

Colour Change

Visible colour changes can be conveniently group under two heads—physiological and morphologic Physiological changes are those which involved red tribution of pigment only; morphological chang involve absolute loss or gain of pigment.

Physiological Change.—With the exception insects, animals that exhibit this type of change ha their pigment localized in cells (or vesicles) cal chromatophores (q.v.). Chromatophores react to

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HYDROGEN-UTILIZING, SULFATE-REDUCING BACTERIA IN MARINE SEDIMENTS[1]

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Received for publication August 21, 1950

Molecular hydrogen is utilized under anaerobic conditions by several physiological types of bacteria (ZoBell, 1947), among which sulfate reducers appear to be the most important in marine sediments. Although the observations of Nikitinsky (1907), Kroulik (1913), and Niklewski (1914) suggested that certain sulfate-reducing bacteria oxidize hydrogen, it remained for Stephenson and Stickland (1931*a*,*b*) to establish the utilization of molecular hydrogen by such bacteria. The autotrophic activity of hydrogen-oxidizing sulfate reducers was reported by Wight and Starkey (1945) and by Butlin and Adams (1947).

Hydrogen-consuming sulfate reducers have been detected in water or soil by Stephenson and Stickland (1931*a*), Von Wolzogen Kühr and Van der Vlugt (1934), Pont (1939), Ménard and Berkalof (1940), Pomeroy (1945), Starkey and Wight (1943), Wight and Starkey (1945), Butlin *et al.* (1947, 1949), and Postgate (1949). Finding such bacteria in marine bottom deposits and in petroliferous sediments led ZoBell (1947) to believe that the activities of sulfate reducers might help to account for the general absence of free hydrogen in environments where the fermentation of organic matter and other chemical or physical processes tend to liberate hydrogen. Hydrogen-consuming sulfate reducers might also be important geochemical agents (ZoBell and Rittenberg, 1948). The present study is concerned primarily with a survey of the occurrence and abundance of hydrogen-utilizing, sulfate-reducing bacteria in marine sediments both recent and ancient. Pure cultures of such bacteria have proved to be species of *Desulfovibrio.*

MATERIALS AND METHODS

The bacteria were cultivated in sea water enriched with 0.5 per cent $MgSO_4 \cdot 7H_2O$ and 0.01 per cent $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$. Following autoclave sterilization the reaction of the medium was adjusted to pH 7.5 and the redox potential to about E_h −100 mv by adding per liter 20 ml M/1 $NaHCO_3$, 5 ml M/1 KH_2PO_4, and 10 ml M/10 Na_2S. The sea water employed in the preparation of the mineral solution for demonstrating autotrophic sulfate reducers contained less than 1 mg per L of organic matter.

With aseptic technique, sterile 125-ml glass-stoppered bottles (figure 1) are filled three-fifths full of sterile mineral solution. Then, after the inoculum is introduced into culture bottle *A*, the bottles are connected with the glass siphon with all three stopcocks open. Air is displaced from bottle *A* by filling the latter with solution from bottle *B*, after which hydrogen, passed through a train to remove oxygen and bacteria, is forced into bottle *A* until bottle *B* is filled to capacity with the mineral solution. The bottles are then incubated at 28 C with

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 490. This paper is a contribution from American Petroleum Institute Research Project 43A.

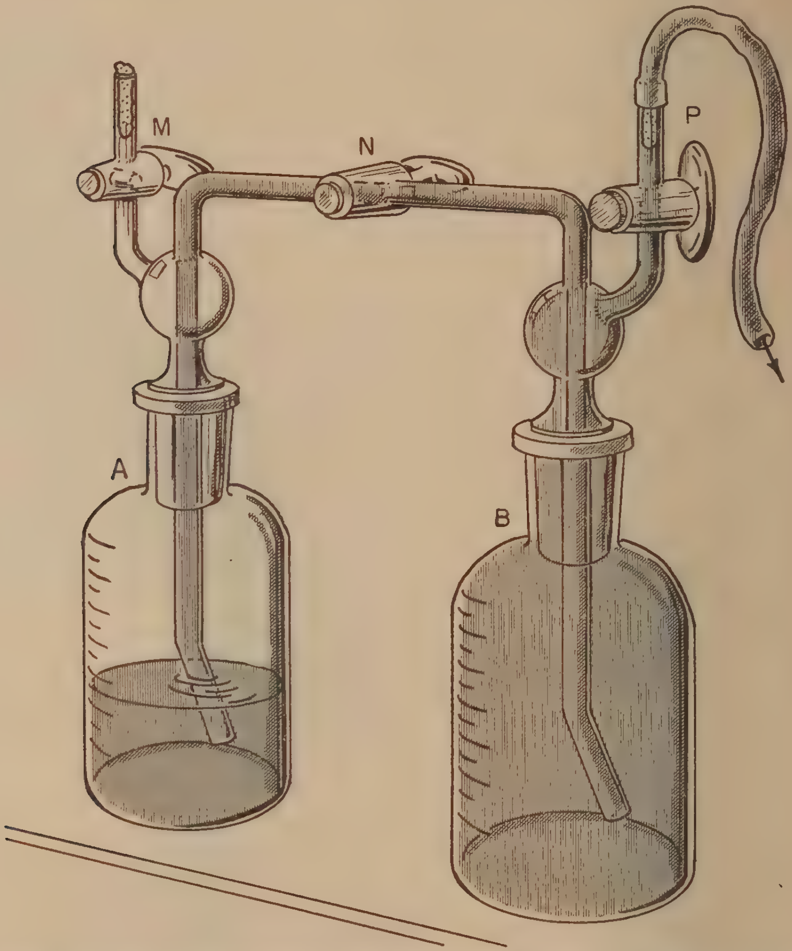

Figure 1. A pair of 125-ml glass-stoppered bottles with connecting siphon for following the utilization of molecular hydrogen by sulfate-reducing bacteria. The outlet tubes on stopcocks *M* and *P* are plugged with cotton in order to help prevent contamination. The outlet tube on stopcock *P* is connected with a train of wash bottles one of which contains alkaline pyrogallol to remove oxygen from air aspirated into reservoir bottle *B* as mineral solution is siphoned into culture bottle *A* when the culture consumes hydrogen.

stopcock *M* closed and stopcocks *N* and *P* open. As hydrogen is consumed, mineral solution is siphoned from bottle *B* into bottle *A*. Graduation marks on the bottles make it possible to read the volumes at constant temperature and corrected atmospheric pressure. Thus gas uptake can be followed without interrupting the experiment. At the termination of our experiment the residual gas was analyzed by the Orsat apparatus or, in some cases, by mass spectrometer, the latter analyses being made by courtesy of the Richfield Oil Corporation laboratories at Wilmington, California.

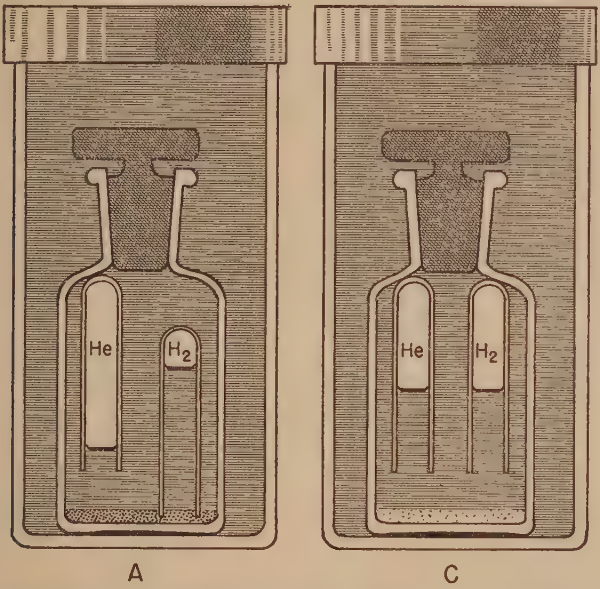

Figure 2. Glass-stoppered bottles containing vials of gas and mineral solution for the growth of autotrophic sulfate-reducing bacteria, incubated immersed in screw-cap jars containing the same solution. At the beginning of the experiment, as in uninoculated controls (*C*), one of the inverted vials is partly filled with helium and the other with hydrogen. When growth has occurred, most of the hydrogen is consumed, the helium is more rarefied, and a floc of ferrous sulfide intermixed with bacteria occurs in the bottom of bottle *A*.

Hydrogen sulfide resulting from the reduction of sulfate:

$$H_2SO_4 + 4H_2 \rightarrow H_2S + 4H_2O$$

reacts with ferrous iron in the mineral solution to render it progressively darker in color as black ferrous sulfide is formed:

$$H_2S + FeSO_4 \rightarrow FeS + H_2SO_4$$

The sulfide helps to maintain the anaerobic conditions so essential for the functioning of autotrophic species of *Desulfovibrio.*

Autotrophic hydrogen oxidation by sulfate reducers was also demonstrated in 60-ml glass-stoppered bottles, each containing two inverted 3-ml vials (figure 2), one containing hydrogen and the other helium. Since a negative pressure resulted from the consumption of hydrogen, these bottles were incubated immersed in wide-mouth, screw-cap jars filled with sterile mineral solution, thereby preventing the introduction of air into the system. Since the sulfate reducers are obligate anaerobes, rigorous precautions must be exercised to maintain reducing conditions.

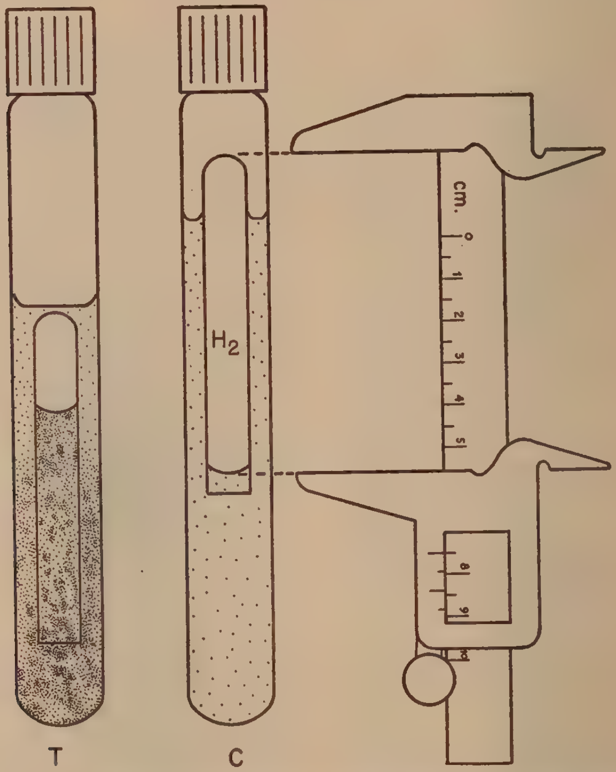

Figure 3. Screw-cap test tubes with inverted vials containing hydrogen alongside calipers for estimating the amount of hydrogen consumed by heterotrophic sulfate-reducing bacteria in tube *T* by comparing it with the uninoculated control *C*.

For the demonstration of hydrogen consumption by heterotrophic sulfate reducers a medium having the following composition was employed:

K_2HPO_4	0.2 g	Ascorbic acid	0.1 g
$MgSO_4 \cdot 7H_2O$	0.2 g	Calcium lactate	3.5 g
$(NH_4)_2SO_4$	1.0 g	Difco neopeptone	1.0 g
Na_2SO_3	0.1 g	Difco agar	3.0 g
$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$	0.1 g	Sea water	1,000.0 ml

The medium was dispensed in 30-ml, screw-cap test tubes containing inverted vials that were filled with hydrogen (figure 3). Hydrogen utilization was indicated by the disappearance of the gas from the inverted vials in an amount exceeding that in the uninoculated controls. Sulfate reduction was indicated by the blackening of the medium due to the formation of ferrous sulfide.

The two kinds of media were inoculated with approximately 1 gram of marine sedimentary material or dilutions (1:10, 1:100, etc.) thereof. A total of 245 carefully collected samples were examined in this manner. Recent sediments came from various parts of the Antarctic, Arctic, Atlantic, and Pacific oceans as well as from bays, estuaries, and marine marshes. Samples of ancient sediments were obtained from oil wells through the co-operation of oil companies and the American Petroleum Institute.

RESULTS

From 2 to 5 weeks' incubation at 28 C was required for the bacteria in the mud samples to consume detectable quantities of hydrogen (table 1). Occasionally selective media inoculated with mud exhibited evidence of hydrogen uptake only after 16 to 24 weeks' incubation, but the majority of the samples that ever became positive did so within a month. As soon as there was definite evidence of hydrogen uptake, a loopful of the culture was inoculated into another bottle of sterile inorganic medium in order to eliminate organic matter and to establish the autotrophic nature of the organisms, four or more such transfers being made seriatim. Such enrichment cultures generally consumed detectable quantities of hydrogen within a week.

The results of examining a total of 245 sediment samples in this way are as follows:

Hydrogen utilization in		*Sulfate reduction in*	
Inorganic medium	*Organic medium*	*Inorganic medium*	*Organic medium*
108 or 44%	150 or 61%	145 or 59%	187 or 76%

Finding sulfate reduction in a larger percentage of samples than hydrogen utilization in organic medium is a commentary on the fact that in these tests hydrogen sulfide formation was more readily detectable than hydrogen uptake. Since molecular hydrogen was the only available source of energy for bacteria in the inorganic medium, sulfate must have been reduced at the expense of such hydrogen. Actually subculturing the sulfate reducers from the inorganic medium established that they could utilize molecular hydrogen. As will be detailed in a subsequent paper, several cultures of sulfate reducers have been subcultured numerous times in inorganic medium enriched with molecular hydrogen as the only source of energy, and resting cells of some have been used to study the rate of hydrogen uptake in Warburg microrespirometers.

Finding a larger percentage of hydrogen utilization in organic medium than in inorganic medium has at least two explanations. First, the organic constituents might enhance the growth of certain hydrogen-utilizing sulfate reducers, and, second, bacteria are present in certain sediment samples that consume hydrogen by the reduction of organic compounds. Hoogerheide and Kocholaty (1938) have reported the relative rates at which various amino acids and related substances were hydrogenated by molecular hydrogen by suspensions of *Clostridium sporogenes*. The bacterial hydrogenation of fumarate and related organic compounds has been reported by Farkas and Fischer (1947) and Farkas and Schneidmesser (1947). Additional examples of the microbial reduction of organic substances with molecular hydrogen are given by Wieland and Pistor (1938), Stephenson and Stickland (1933), and ZoBell (1947). Also, molecular hydrogen might be utilized in the reduction of carbon dioxide to methane, as discussed by Barker (1943) and Kluyver and Schnellen (1947). As a matter of fact, methane was quite commonly detected in our enrichment cultures that had grown in organic medium as well as in cultures developing in inorganic medium:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

Tests on enrichment cultures from marine sediments, however, showed that sulfate reduction accounts for most of the hydrogen consumption in both the organic and inorganic media used in these experiments.

Distribution of marine hydrogen utilizers. The widespread geographic distribution of hydrogen-utilizing sulfate reducers is illustrated by the data in table 2. The ancient marine sediment samples came from oil wells in Texas, California, and Oklahoma, some from depths of several thousand feet. A good many of the samples of ocean bottom deposits came from depths of several hundred feet below the water surface and some from appreciable depths below the mud-water interface (table 3). Test borings for coastal pilings provided mud samples from depths as great as 181 feet, some of which contained hydrogen-consuming, sulfate-reducing bacteria. The marine marsh samples (tables 2 and 3) were collected along the coasts of California, Louisiana, and Cuba.

TABLE 1

H_2 uptake and H_2S production in different types of media inoculated with decreasing amounts of marine mud sample no. 43:11 after different periods of incubation at 28 C

AMOUNT OF MUD IN GRAMS	AUTOTROPHS IN MINERAL MEDIUM				HETEROTROPHS IN ORGANIC MEDIUM			
	Two weeks		Five weeks		Two weeks		Five weeks	
	H_2	H_2S	H_2	H_2S	H_2	H_2S	H_2	H_2S
1.0	+	+	+	+	+	+	+	+
0.1	+	+	+	+	+	+	+	+
0.01	+	+	+	+	+	+	+	+
0.001	−	−	+	+	−	+	+	+
0.0001	−	−	−	+	−	+	+	+
0.00001	−	−	−	−	−	−	+	+
None (control)	−	−	−	−	−	−	−	−

Some of the ancient marine sediment samples came from oil wells at depths as great as 9,000 feet. Sulfate-reducing bacteria found in such sediments, like some of those isolated from the deep-sea floor, have been found to be active at hydrostatic pressures isobaric with these depths, roughly 300 atmospheres at 9,000 feet. This observation tends to substantiate our belief that such baroduric (pressure-tolerant) bacteria are species indigenous to these great depths, since most bacteria isolated from near-surface material are inhibited by high pressure (ZoBell and Johnson, 1949). Certain sulfate reducers have proved to be obligate barophiles active only at pressures of 300 to 600 atmospheres.

TABLE 2

Number of samples of marine sediments from various geographic regions showing the presence of bacteria in 1-gram inocula that consumed molecular hydrogen or reduced sulfate, or both, in different kinds of media

SOURCE OF SEDIMENT SAMPLES	NUMBER OF SAMPLES EXAMINED	H_2 UTILIZATION IN		SO_4 REDUCTION IN	
		Organic medium	Inorganic medium	Organic medium	Inorganic medium
Arctic Ocean	40	24	11	31	15
Antarctic Ocean	5	2	0	1	0
Pacific Ocean	53	32	23	43	34
Caribbean Sea	2	2	1	2	1
Gulf of Mexico	24	24	16	24	18
Marine marshes	63	48	41	63	54
Ancient marine	58	18	16	23	23

TABLE 3

Vertical distribution of hydrogen-consuming and sulfate-reducing bacteria detected in 1-gram samples of marine sediments from various sources

DEPTH IN FEET	NUMBER OF SAMPLES EXAMINED	H_2 UTILIZATION IN		SO_4 REDUCTION IN	
		Organic medium	Inorganic medium	Organic medium	Inorganic medium
Water depth					
0–50	59	47	43	49	49
50–500	43	27	17	24	21
500–10,000	13	8	5	6	6
Core depth					
0–1	90	72	64	83	71
1–3	20	10	8	7	7
3–10	16	4	2	2	2
10–181	22	9	9	11	11

TABLE 4

Occurrence of hydrogen-utilizing and sulfate-reducing bacteria in 1-gram samples of a core of marine sediments (29:186) representing different core depths

CORE DEPTH IN FEET	DESCRIPTION OF SEDIMENT	H_2 UTILIZATION IN		SO_4 REDUCTION IN	
		Organic media	Inorganic media	Organic media	Inorganic media
1	Sandy clay	+	+	+	+
17	Sandy clay	+	+	+	+
37	Sandy silt	+	+	+	+
77	Blue clay & sand	−	+	+	+
97	Blue clay	−	+	+	+
117	Sand	−	−	+	−
137	Clay & sand	−	−	−	−
157	Clay & sand	+	−	+	−
181	Clay & sand	−	+	+	+

A larger percentage of positive results was obtained with the topmost portions of marine mud samples than in those from greater depths. Hydrogen-utilizing sulfate reducers appear to occur quite commonly in the upper layers of recent marine sediments, but at greater depths such bacteria occur only sporadically and in far smaller abundance. The minimum dilution method indicated the presence of from 0 to 100 viable hydrogen utilizers per gram of mud taken from depths below 1 foot as compared with counts ranging up to 10,000,000 per gram in the topmost foot of mud.

The sporadic occurrence of hydrogen-utilizing and sulfate-reducing bacteria in a long core of recent marine sediments is illustrated by the data in table 4. This core material was collected by the Humble Oil and Refining Company at Tiger Pass in the tidewater area of Louisiana. Aseptic precautions were exercised in handling the material, and only radially central subsamples of the core untouched by anything except laboratory-sterilized instruments were used to inoculate enrichment media.

DISCUSSION

Evidence for the general occurrence of sulfate reducers in marine sediments has been summarized by ZoBell and Rittenberg (1948). Many of these bacteria have been shown to be able to utilize molecular hydrogen. That sulfate-reducing bacteria are physiologically active *in situ* is indicated by a decreasing concentration of sulfate and an increasing concentration of sulfide, with depth or geological age of marine sediments and brines associated with petroleum. Though there may be other mechanisms to account for the reduction of sulfate, the presence of living bacteria offers the most plausible explanation, particularly since the nutrients and environmental conditions in the sediments have been shown to be conducive to the activity of sulfate reducers. The latter may also help to account for the observed decrease with depth or modification of the organic content of sediments. Besides being able to utilize several kinds of organic compounds (Baars, 1930), which may occur in marine sediments, certain sulfate-reducing bacteria attack petroleum hydrocarbons (Tausson and Aleshina, 1932; Tausson and Vesselov, 1934; ZoBell, 1950).

Bastin and his co-worker (1926, 1930) found sulfate-reducing bacteria in 28 oil field waters out of 30 sampled in Illinois and in 15 out of 37 sampled in California at depths ranging from 400 to 1,866 feet. Similar observations were made by Gahl and Anderson (1928) and by Ginter (1930, 1934). Upon finding such bacteria in 14 out of 15 samples of oil sands from the Grozny marine formation, Ginsburg-Karagitscheva (1933) attributed the abundance of hydrogen sulfide and the low concentration or lack of sulfate in water from oil wells to the activity of sulfate reducers. Such bacteria may utilize sulfate as a hydrogen acceptor while oxidizing organic matter or petroleum hydrocarbons as an energy source. The present studies show that molecular hydrogen may also serve as an energy source.

Hydrogen may be formed in marine sediments from the fermentation of the organic remains of plants and animals, or it may result from a variety of chemical or physicochemical reactions (ZoBell, 1947). Its general, though not complete, absence from natural gases in marine sediments where one might expect to find free hydrogen may be due in part to the activities of sulfate-reducing bacteria that consume hydrogen.

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SUMMARY

Methods are described for demonstrating the utilization of molecular hydrogen by sulfate-reducing bacteria under strictly anaerobic conditions.

Hydrogen-utilizing sulfate reducers were found in about half of the 245 one-gram samples of marine sediments examined from different parts of the world. Such bacteria were more abundant in sediments near the mud-water interface than at greater depths, although some were found a few thousand feet below the surface.

Autotrophic sulfate reducers that utilize hydrogen as a source of energy were demonstrated in several enrichment cultures. Pure cultures have proved to be species of *Desulfovibrio*.

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